ACID PRECIPITATION RESEARCH IN CANADA

JULY 1989

Environment Ontario

Jim Bradley
Minister

ISBN: 0-7729-5675-8

ACID PRECIPITATION RESEARCH IN CANADA

Report prepared by:
J.C. Keith and P.J. Dillon

Dorset Research Centre

JULY 1989

RECYCLABLE

Table of Contents

Table of Contents (cont'd)

ABSTRACT

The deposition rate of strong acid in eastern Canada is similar to or greater than that documented in Norway and Sweden. Since the mid 1970's, Canadian provincial and federal agencies have been studying the effects of acid deposition on atmospheric processes and on terrestrial, and aquatic systems. Research results have consistently supported the Canadian position that reductions in sulphur dioxide emissions are needed across eastern North America to protect sensitive environments.

1.0 INTRODUCTION

1.1 History of the Acid Precipitation Problem in Canada

For several decades, Canadian scientists have been aware of the environmental damage to terrestrial and aquatic systems that can result from SO_2 emissions from point sources. In fact, the first reported case (Anon. 1941) was actually a transboundary pollution problem. Sulphur dioxide emissions from a smelter located in Trail, British Columbia caused environmental damage to areas across the border in the state of Washington (see Figure 1 for a map of Canada and its areas that are sensitive to acid deposition). This case set a legal precedent which will be discussed later in this Section.

The acidification of lakes in Canada was first described in the Province of Ontario in the Sudbury area in the early 1950's. Nickel and copper smelting operations began in the Sudbury geological basin in 1888. Smelter production increased throughout the 1930's, then again in the 1950's and the 1960's, resulting in continuous increases in the emissions of sulphur compounds and metals, especially copper and nickel. The INCO Limited smelter was, for many years, the world's single largest point source of SO_2 emissions and remains the largest in North America. Nearly a century of smelting operations resulted in the destruction of the local forests and other vegetation as a consequence of the high SO_2 concentrations, and severe damage to many of the local lakes. After the lakes had exhausted their acid neutralizing capacities, acidification to pH's of approximately 4.0 and elevation of metal (Cu, Ni, Zn) concentrations to toxic levels resulted.

In the 1960's, studies began to document the extent of the damage. Beamish and Harvey (1972) showed that 70 of 150 lakes in the La Cloche Mountain area (approximately 50 to 100 kilometres south-west of Sudbury) had pH levels less than 5.5. These lakes had lost populations of lake trout and white sucker (Beamish 1974a; 1974b; Beamish et al.

1975). In addition, many lakes to the north-east of Sudbury were found to be equally acidic.

Pollution from a local source was also responsible for the acidification of the surrounding environment at Wawa, Ontario. In 1939, the Algoma Steel Corporation began open-pit iron ore mining and smelting operations in the area. With the discovery of high-quality underground deposits, mining activities expanded in 1949, 1954 and 1958, resulting in the abandonment of the open-pit mines in favour of the underground iron reserves. The SO_2 fumigations and associated acid precipitation resulted in acute toxic effects to the birch, spruce and pine forests within approximately 900 km^2, as well as degradation of lake chemistry and losses of fish populations within 65/m^2. Within a zone of 200 km^2, deposition of acid has maintained lake pH levels between 3.0 to 4.0 for nearly 20 years (Somers and Harvey 1984).

These cases of environmental damage from acid emissions have all resulted from local point sources. It was not until the mid 1970's that acidification was also considered to be a regional problem resulting from the long-range transport of air pollutants.

In 1975, the Ontario government began a detailed study of lakes in Muskoka-Haliburton (a popular recreational area approximately 250 km north-east of Toronto) with the objective of determining the effects of cottage development on water quality. Researchers soon discovered that atmospheric loadings of acid were elevated in this area and that there was evidence of water quality effects including loss of alkalinity and lowering of pH in lakes located in the region (Dillon et al. 1978).

Continued research in Ontario and the other eastern Canadian provinces soon demonstrated that the Muskoka-Haliburton area in Ontario was not the only region affected by long-range transport of sulphur oxides. A large portion of eastern Canada is underlain by the Precambrian Shield which is characterized by granitic and siliceous bedrock of limited

acid neutralizing capacity. Areas in Canada considered sensitive to acid deposition based on underlying bedrock are shown in Figure 1.

Another important factor in determining the effect of acid deposition on a specific area is the area's location with respect to emission sources. Over most of north-eastern North America, the prevailing winds travel in a north-easterly direction and carry with them the pollutants generated in the midwestern American industrialized heartland. The wind pattern does vary to some extent with the season and there are often air flows to the south in the winter. As a result, pollutants generated in Canada can also be transported across the border to the United States. Still, the transboundary flux of pollutants from the United States to Canada exceeds the flux from Canada to the United States by a factor of approximately three or four (RMCC 1986), principally because of the fact that total United States emissions of both sulphur and nitrogen are much greater (RMCC 1986).

The extreme sensitivity of the Canadian aquatic environment has resulted in great concern within Canada about the environmental consequences of continued high loadings of strong acids and their precursors. The transboundary nature of the problem increases the complexity of solving the problem but does not make a resolution impossible to achieve.

A legal precedent regarding transboundary pollution was established by the Trail Smelter case in 1941. Sulphur dioxide emissions from a smelter constructed in Trail, British Columbia in the late 1890's resulted in extensive damage locally, as well as in areas across the border in the State of Washington. The initial dispute involved a private nuisance claim against a corporation in Canada by residents of the State of Washington. Although the dispute did not directly concern the two governments, they agreed to submit it to an Arbitral Tribunal established pursuant to an international convention. It was accepted that Canada would be responsible for any damage caused by the corporation and the United States was the proper claimant to represent

claims by its citizens. In April 1935, a preliminary agreement on compensation to the residents was reached and a final resolution on pollution control at the smelter was established in 1941. The Trail Smelter Arbitration (1941) established the following important international legal principle:

> "... no State has the right to use or to permit the use of its territory in such a manner as to cause injury by fumes in or to the territory of another or the properties or persons therein when the case is of serious consequence and the injury is established by clear and convincing evidence."[1]

Whatever the international interpretation of this law, it has a special claim to recognition by judicial and administrative tribunals in the United States and Canada.

1.2 History of Negotiations on Transboundary Air Pollution with the United States

In 1976, the Canadian Network for Sampling Precipitation (CANSAP) began monitoring the acidity of rainfall. The results showed that in Canada, the deposition rate of strong acids was similar to that documented in Norway and Sweden (Summers and Whelpdale 1976). Simultaneously, research in southern Ontario (Dillon et al. 1978) showed that deposition of acid and sulphate greatly exceeded that provided by any local sources.

In 1978, in recognition of the transboundary nature of the problem, the Governments of the United States and Canada established a United States/Canada Bilateral Research Consultation Group to study the LRTAP

---

[1] Am. J. of Int. Law, 1941.

phenomenon and to co-ordinate research between the two countries. Furthermore, in November of that same year, the United States sent Canada a diplomatic note requesting an informal discussion of a Congressional Resolution calling for a co-operative agreement with Canada on transboundary air pollution. The United States was concerned about the potential environmental impacts of a new coal-fired power plant at Atikokan in north-western Ontario on the Boundary Waters Canoe Area in Minnesota.

In 1979, Canada and the United States issued a joint statement on transboundary air quality announcing the intention of both governments to develop a co-operative agreement on air quality. After continued discussions between the two countries, Canada and the United States signed a Memorandum of Intent in August of 1980 concerning transboundary air pollution. In this document, both countries declared their intention:

> "to develop a bilateral agreement which will reflect and further the development of effective domestic control programs and other measures to combat transboundary air pollution"[2]
>
> and
>
> "to promote vigorous enforcement of existing laws and regulations as they require limitation of emissions from ... existing facilities in a way which is responsive to the problems of transboundary air pollution."[3]

---

[2] Canada/United States Memorandum of Intent, August 5, 1980.

[3] Ibid.

In addition, five working groups were established to provide the scientific basis of this agreement. While the working groups continued to meet and discuss the relevant scientific findings, several negotiating sessions were held between the two countries. At the February 25, 1982 negotiating meeting the Canadian federal Environment Minister announced that Canada was prepared to reduce its SO_2 emissions by 50% east of the Manitoba/Saskatchewan border, contingent on a similar commitment by the United States. At the June 15, 1982 session, United States negotiators rejected Canada's proposal. As a result, the Canadian federal Environment Minister decided that future negotiations with the United States would be fruitless and broke off official negotiations.

However, the final work group reports were released in February of 1983 and subsequently reviewed. The United States peer review which was conducted by the National Academy of Sciences called for reductions in acid emissions and rejected the argument that more research was needed before control action could be taken. The Canadian peer review report was released by the Royal Society of Canada and concluded that the scientific evidence was sufficient to warrant prompt introduction of abatement measures.

With the failure of the MOI negotiations and the continued concern expressed by the Canadian government, President Reagan agreed to the appointment of special envoys by the two governments to review and assess the international environmental problems associated with the long range transport issue and to recommend actions to resolve them. The Joint Report of the Special Envoys on Acid Rain was released in January of 1986 prior to the second summit meeting between Prime Minister Mulroney and President Ronald Reagan. It called for the implementation of a five-year, five-billion-dollar control technology demonstration program by the United States government with joint funding between the government and private industry (Lewis and Davis 1986). In addition, it recommended that both countries review existing air pollution legislation to identify opportunities for addressing

transboundary environmental concerns and that they establish a bilateral advisory and consultative group on transboundary air pollution. Both countries accepted the Envoys' Report at the 1986 summit meeting.

Since that time, several meetings have been held by the Bilateral Advisory Group and the commitment to the Envoys' Report was reaffirmed at the 1987 Summit. However, the United States Administration continued to express its reluctance to take abatement action, insisting that more research is needed before emissions reductions can be mandated. In 1985, Canada announced its intention to reduce emissions by at least 50% east of the Manitoba/ Saskatchewan border by 1994 with the Provinces of Quebec, Ontario and Manitoba subsequently issuing regulations to major SO_2 emitters within their jurisdiction in order to fulfill their commitments. By 1988, comparable action had not been taken by the United States.

2.0 ATMOSPHERIC STUDIES

2.1 Emissions

2.1.1 SO_2 and NO_X Emissions Inventories

The compilation of up-to-date emissions inventories for acid-producing pollutants is necessary for several reasons. Historic and current databases allow us to determine if any emission trends are developing. Detailed and accurate emission inventories are needed for input to atmospheric transport models and for the development and implementation of successful control programs.

The 1980 emissions inventory for SO_2 and NO_X from anthropogenic sources is currently the most complete for both Canada and the United States. Total SO_2 emissions in Canada in 1980 were

estimated at 4.6 million tonnes (RMCC 1986). In eastern Canada, six large copper and nickel smelters (two in Manitoba, two in Ontario and two in Quebec) and one iron ore processing plant (in Ontario) together produced about 45% of the total (Figure 2). Electric utilities accounted for another 16.5% with substantial emissions in three provinces, Ontario, New Brunswick and Nova Scotia. Regionally, the provinces east of the Manitoba/Saskatchewan border accounted for more than 80% of the Canadian total (RMCC 1986).

Total NO_x emissions in Canada in 1980 were 1.7 million tonnes (RMCC 1986). Mobile sources (cars, light-duty trucks, etc.) are the most significant source of NO_x in Canada, accounting for about two-thirds of the emissions in eastern Canada, with the remainder caused by power plants and other sources. NO_x emissions are more evenly distributed spatially than SO_2 emissions, but the eastern part of the country is still the major source area at approximately 60% (RMCC 1986).

The national inventory also includes estimates of other species such as VOC's (Volatile Organic Compounds), primary sulphates and particulates.

Work is nearing completion on the development of a complete emissions inventory for 1985 for both Canada and the United States.

Due to the shortage of actual measurements, there is a degree of uncertainty in the estimates of natural emissions of SO_2 and NO_x. In 1980, it was estimated that sulphur emissions from natural sources were approximately 0.5 million tonnes, principally from the biogenic activity of soils (RMCC 1986).

Estimates for NO_x emissions from natural sources in Canada are currently not available. The United States National Oceanic and Atmospheric Administration estimated the total annual natural NO_x emissions in North America at 0.9 million tonnes (N), 0.3 million tonnes (N) as a result of lightning and 0.6 million tonnes (N) from soils (RMCC 1986).

2.1.2 Trends in SO_2 and NO_x Emissions

Canadian SO_2 emissions in 1955 were approximately 4.6 million tonnes. They rose to a peak of 6.7 million tonnes between the mid-1960's and 1970, then decreased back to 4.6 million tonnes in 1980 (RMCC 1986). Eastern Canada continued to be the major contributor to these SO_2 emissions throughout this period. Subsequent to 1980, emissions have dropped in eastern Canada. SO_2 emissions in eastern Canada were approximately 3.2 million tonnes in 1984, down from 3.8 million tonnes in 1980 (RMCC 1986; Dillon et al. 1988; Figure 3).

During the same time period, Canadian NO_x emissions have increased from 0.6 million tonnes in 1955 to 1.7 million tonnes in 1980. Unlike SO_2 emissions, Canadian NO_x emissions have remained relatively constant since 1980 (RMCC 1986; Dillon et al. 1988; Figure 3).

With the recent announcements of regulations mandating SO_2 emissions reductions by several of the eastern Canadian provinces, it is estimated that SO_2 emissions in eastern Canada (east of the Manitoba/Saskatchewan border) will be reduced by at least 50% by 1994 to 1.85 million tonnes. Furthermore, with the new motor vehicle standards for NO_x effective in the fall of 1987 on 1988 model-year vehicles, NO_x emissions are expected to level off in Canada.

2.2 Deposition Monitoring

2.2.1 Wet and Dry Deposition

Several federal and provincial networks have been established to monitor the concentration and deposition rates of chemical species in precipitation on both local and regional scales (Table 1). Short-term as well as long-term spatial and temporal variations in wet deposition are under study. A National Atmospheric Data Base (Natchem) is being implemented as a repository for the Canadian data.

Figure 4 shows the wet deposition patterns of sulphate across eastern North America from the combined results of Canadian and American monitoring networks. The southern portions of the provinces of Ontario and Quebec currently receive the highest deposition rates of strong acid in Canada with the Maritime provinces receiving higher deposition rates than the western provinces (where wet sulphate deposition is on average below 10 kg ha^{-1} yr^{-1}).

Several of the monitoring networks described in Table 1 originally attempted to collect dryfall as well, using both 'wet' and 'dry' buckets. However, an analysis of the results suggested that for sulphur and nitrogen compounds, the dryfall thus determined was not representative of dry deposition. At present, dry deposition is inferred from air concentration data which are measured at numerous sites cross Canada by both federal and provincial agencies. The dry deposition rate is then calculated by multiplying the air concentration by a deposition velocity which is determined for each substance taking into account information on local meteorology and surface characteristics.

In Canada, the APN (Air and Precipitation Monitoring Network) was set up specifically to obtain ambient air concentrations of selected S and N compounds and precipitation chemistry at rural sites. This network was expanded and became the Canadian Air and Precipitation Monitoring Network (CAPMoN). Results from the APN sites showed that ambient SO_2 concentrations decreased with increasing distance from the major sources. An analysis of four years of air and precipitation chemistry measurements (Summers et al. 1986) at six locations in eastern Canada indicated that dry deposition of sulphur accounted for 22% of the total sulphur deposition and dry deposition of nitrogen accounted for 21% of the total nitrogen deposition. On average, dry deposition accounted for about 40% of the total deposition at the southernmost stations, but less than 20% in remote areas.

Ontario's airborne particulate and SO_2 sampling network consists of more than 20 sites with low-volume sampling carried out over four-week intervals to determine ambient concentrations of various particulate and gaseous compounds, as well as daily measurements at four sites. In southern Ontario, the dry deposition is about one-half of the wet deposition rate whereas in central and northern Ontario it is about one-quarter to one-fifth of the wet deposition rate (Tang et al. 1986).

There are various additional special studies of atmospheric deposition in progress in Canada, including eddy correlation studies of dry deposition of SO_2 and O_3 to forest stands at Borden, Ontario (den Hartog et al. 1987) and of NO_2 and SO_2 to agricultural crops and snow surfaces (Edwards and Ogram 1986, Ogram et al. 1988), instrument intercomparisons and evaluations at a number of sites, and the sampling of trace metals in air and precipitation at Muskoka in order to assess the impact of smelting activities in Sudbury.

2.2.2 Variability in Deposition Measurements

Deposition of sulphate and many other ions exhibits a strong seasonal cycle which is related to the seasonal nature of many meteorological and chemical processes. Studies by Tang et al. (1986) at Dorset, Ontario and Summers (1986) in the central and maritime Canadian regions show that maximum deposition of sulphate occurs during the summer months, and that nitrate shows minimal variation between winter and summer periods.

In North America, major precipitation episodes with high rates of wet deposition can account for a large fraction of the annual total deposition. A four-day event in 1981 in Muskoka, Ontario contributed 7 kg of wet sulphate (28%) to the annual total (Kurtz et al. 1984).

Over a long period of time (a year or more), it appears that, for many eastern Canadian locations, 20% of these storm events can contribute between 47 and 70% of the total wet and dry deposition of sulphate and nitrate (Barrie and Sirois 1986). For sulphate, the contribution by single events is higher for wet deposition than for dry, particularly at remote locations, whereas for nitrate, the reverse is true (Barrie and Sirois 1986).

The amount of atmospheric deposition varies from year to year due to several factors including changes in emission rates and meteorological variability making trend analyses very difficult.

However, Canadian agencies that have sufficient data available have conducted trend analyses.

Analysis of data from five rural sites in Nova Scotia between 1978 and 1984 (Underwood 1985) showed some temporal trends with

decreases in deposition of sulphate, nitrate and hydrogen ion over recent years.

In an analysis conducted by Dillon et al. (1988), the results of ten years of bulk deposition monitoring in the Muskoka-Haliburton area were reported. The recent decrease in SO_2 emissions in eastern North America was strongly correlated with a concomitant decrease in both bulk deposition rates and concentration of sulphate and hydrogen ions. Similar results were reported by Hedin et al. (1987) for the north-eastern United States. These long-term data records demonstrate the benefits of emissions controls.

Recent sampling of fogs and low clouds have also shown high concentrations of strong acid anions and extremely low pH's. Measurements made by aircraft in central Ontario show a strong tendency for the lowest pH to occur at the cloud base with pH values typically ranging from 3.0 to 5.0 (Summers et al. 1985). The associated sulphate and nitrate concentrations range from 10 to 50 mg per litre in polluted air masses. Extreme values of 60 mg per litre have been recorded in summer convective clouds in Ontario (Leaitch et al. 1986).

Recently, a network of mountain monitoring sites has been established (CHEF - Chemistry of High Elevation Fogs) as a forest project with similar sites in the United States to monitor air, fog and precipitation chemistry. Preliminary data from the Canadian sites indicate that fog (cloud on the mountain) water pH values (mean 3.7) near the summits are much lower than precipitation pH values (mean 4.3) at the same location (Schemenauer 1986; Schemenauer and Winston 1988).

2.3 Meteorological and Modelling Studies

2.3.1 Meteorological Studies

Numerous studies have been carried out related to acidic deposition and long-range transport. One example is an overview study on meteorological analyses of precipitation events in Ontario for the period 1976 to 1983 (Yap and Kurtz 1986) which indicated that for southern and central Ontario, precipitation events most commonly occur with pre-warm front and cyclonic weather situations, and air parcel trajectories from the south and south-west octants. Trajectories from these octants, which include the heavily industrialized regions of the Ohio Valley and south-western Ontario, also account for most of the wet deposition of sulphur and nitrogen.

This technique was used to assess the impact of a major reduction in SO_2 emissions on atmospheric deposition (Lusis et al. 1986). During the period from June 1982 to March 1983, the INCO and Falconbridge smelters at Sudbury, Ontario were shut down. The results of the analysis indicated that for receptors in a 400 km radius of the smelters, the smelter contribution to wet deposition of sulphate is expected to be less than 10 to 15% of the total deposition. For dry deposition of sulphate, the estimated contribution was greater, being about 20 to 30% of the total or less.

Continued collection of pertinent meteorological data is needed to provide support for the analysis of emission reduction effects on atmospheric deposition and for other special studies.

2.3.2 Development of Simple Models

Both the provinces of Ontario and Quebec as well as the federal Atmospheric Environment Service have been involved in the development of simple, linear atmospheric models where physical processes are represented by a small number of variables. These models can be used to evaluate various emission reduction scenarios by predicting the resultant changes in deposition patterns.

In Ontario, two simple long-range transport models have been developed, a statistical model and a Lagrangian or 'trajectory puff' model. The statistical model is used to compute long-term average deposition and air concentration of a chemical specie based on statistical analysis of meteorological variables collected over many years. The Lagrangian model simulates deposition on a monthly and seasonal time scale (Ellenton et al. 1985; Ellenton et al. 1988).

Both the statistical and Lagrangian models have been extensively evaluated, and used in the evaluation of control strategies. Results from modelling exercises have also been presented at various hearings and legal interventions in the United States.

These models have been used to evaluate the benefits of emission controls. As part of the Canadian commitment to reduce SO_2 emissions by 50% by 1994, Ontario announced its control program in December of 1985. This program requires the province's four major producers of sulphur dioxide to reduce their emissions from the 1980 level of 1993 kilotonnes to a maximum of 665 kilotonnes of sulphur dioxide by 1994.

Ontario's statistical model was used to predict the environmental benefits of Ontario's control program. Deposition of wet

sulphate to the province's sensitive Muskoka region would be reduced from the 1980 base case level of 32 kg ha^{-1} yr^{-1} to 27.6 kg, a 14% reduction. The model also predicted significant decreases in deposition in neighbouring regions. For instance, deposition in the sensitive area of southern Quebec would decrease by 10%, in the Adirondacks by 8% and in New Hampshire by 7%.

Simple models have been criticized for numerous reasons, most frequently for their neglect of the non-linear aspects of atmospheric chemistry. Recently, however, these models have been subjected to extensive reviews which concluded that the simple trajectory models appear to simulate wet deposition of sulphur over at least a one-year time period with reasonable accuracy. On this time-scale, the non-linear effects of atmospheric sulphur chemistry are not critical (RMCC. 1986).

2.3.3 Eulerian Model Development

As a result of the numerous criticisms of the usefulness of simple models to predict source-receptor relationships for emission control strategy development, the Ontario Ministry of the Environment and the Canadian federal government entered into a co-operative agreement with the Federal Republic of Germany in 1983 for the development of an Eulerian model, the "Acid Deposition and Oxidants Model" (ADOM). This model will attempt to incorporate all relevant physical and chemical processes in as much detail as possible.

The Canadian Eulerian model is being developed under contract to ERT (Environmental Research and Technology) and includes three-dimensional transport and dispersion, cloud physics, gas and aqueous phase chemistry and detailed treatments of wet and dry scavenging (Venkatram and Misra 1988). As a result, this model will be applicable for episodic studies.

A working version of the model has been installed at the Canadian Meteorological Center (CMC) in Montreal. It has also been installed on the University of Toronto CRAY XMP computer where it is being used to investigate the non-linearity of sulphur chemistry in the atmosphere and the impact of Canadian and United States emission reductions.

Both the Canadian model and its American counterpart, 'RADM' (The Regional Atmospheric Deposition Model), are to be evaluated with monitoring data to be collected during an ambitious field study in Eastern North America during a two-year period starting in June 1988. The objective of this study is not only to determine if the models are predicting acidic deposition rates at the observed levels, but also to determine if they are making the right predictions for the right reasons (i.e. if the chemical and physical processes are correctly simulated).

Once evaluated, ADOM will be applied to investigate the importance of non-linearity in sulphur deposition and to determine the most effective means of controlling various pollutants, including sulphur, nitrogen and hydrocarbons.

3.0 TERRESTRIAL EFFECTS STUDIES

3.1 Soil Studies

3.1.1 Field Studies

The degradation of soils has been documented around major point sources of pollution such as the Sudbury and Wawa, Ontario areas (Whitby et al. 1976). The deposition of toxic metals can also affect the soil to the extent that no tree growth occurs (Linzon and Temple 1980). In addition, sulphur deposition can acidify

soils resulting in the loss of nutrients and the mobilization of aluminum and other toxic elements thereby limiting growth.

The possibility that continued acid deposition could deplete these nutrients and result in less productive forest sites has serious socio-economic consequences since forestry is a 10 billion dollar per year industry in Canada.

Soils common in Canada include luvisols, podzols and brunisols. Although podzols are naturally acidic through the action of carbonic and organic acids, the addition of dilute sulphuric and nitric acids can still result in appreciable effects on water draining these naturally acidic soils, including increased aluminum mobilization (Reuss and Johnson 1985). Acid deposition is more likely to affect soils directly that are less naturally acidic such as luvisols and brunisols.

3.1.2 Laboratory Studies

Field evidence gathered to date suggests that acid deposition can cause increased base cation leaching and Al solubilization (RMCC 1986). Several Canadian studies have been conducted using column-lysimeter leaching experiments to determine the effects of acid deposition on soils common to Canada.

Early experiments which used extremely high loadings of acid showed free movement of hydrogen ion through soils. However, more recent studies have shown that natural soils have considerable ability to buffer hydrogen ion additions. For example, Morrison (1981) observed that both podzol and brunisol soils consumed a considerable amount of hydrogen ion and that throughput of hydrogen ion took place only after soil bases had been substantially depleted. Other Canadian researchers (Hutchinson 1980; Rutherford 1985), using lysimeter studies, have demonstrated that bases are displaced by hydrogen ion, then

transported by sulphate and other anions once the soils are saturated with sulphate.

Additional column-lysimeter work has addressed the question of increased solubilization of aluminum with increased acidity. Aluminum seems to be readily mobilized to high concentrations when the pH of the leaching solution falls sufficiently. In an experiment using a hardwood soil from Ontario and coniferous horizons from Quebec, leaching was limited principally to the upper soil horizons and the solubilized Al was redeposited in the lower soil horizons (Rutherford et al. 1985).

Since it is difficult to determine the influence of acid deposition on soil chemical properties and processes in the field, these experiments allow for the isolation of changes in soil chemistry or processes in the laboratory for comparison with the results of field studies. The combined field and laboratory results should provide a good indication of what is actually occurring in natural soils.

3.2 Vegetation Studies

3.2.1 Lichens and Mosses as Bioindicators

Both laboratory and field studies have indicated that precipitation pH is an important factor in lichen and moss survival (Bailey and Larson 1982). Deposition of airborne pollutants to mosses and lichens in rural areas of Canada has been measured and compared with levels in remote areas (Zakshek and Puckett 1986). Sulphur and lead were the only elements with consistently higher levels in the lichen *Cladina rangiferina* in eastern Canada when compared with levels measured in the Northwest Territories. A comparison of measured sulphur levels in this lichen showed highest values in central Ontario and Quebec, with distinct east-west gradients.

Metal levels in lichens from approximately 50 locations across Canada were strongly influenced by their proximity to major sources of metal contaminated particulates. The sulphur levels of lichens, however, exhibited decreases in concentrations from south to north (Case 1985).

Furthermore, in an experiment subjecting a mature jack pine forest near Kirkland Lake, Ontario to twice monthly applications of acid rain ranging from 2.5 to 5.6 pH over a six year period, the dominant ground cover, the feather moss Pleurozium schreberi, showed significant decrease in percent cover, growth rate and biomass accumulation within two years of all pH treatments below pH 4.0 (Hutchinson and Scott 1986). Substantial decline also was evident in caribou lichens, Cladina spp over the five years of spray applications.

The loss of lichen and moss ground cover will result in exposure of tree roots and soil micro-organisms to drought and other stresses, directly influencing soil chemistry.

3.2.2 Laboratory/Greenhouse Studies

Numerous laboratory and greenhouse experiments have been conducted where different crop and tree species have been subjected to simulated acid rain treatments to determine injury symptoms and to establish visible injury thresholds.

Visible foliar injury is usually manifested by the formation of necrotic spots, pits or lesions on adaxial leaves. Eventually leaves can become deformed or reduced in area and their ability to photosynthesize can become inhibited. This type of injury has been documented in laboratory experiments only at pH of 3.0 or lower.

Greenhouse studies ·(Enyedi and Kuja 1986) showed that crops varied in their sensitivity to acid rain with visible injury occurring on the leaves, stems and flowers of all plants at treatments of pH 3.0. Plant response was also dependent on the total dose of acidity, as well as the characteristics (intensity, frequency and quantity) of the rain event.

Since foliar injury is not a reliable means of assessing actual effects on crop yield, Kuja et al. (1986) conducted a study to determine the effects of simulated acid rain on seed germination, seedling establishment and early stages of plant growth. Again, visible foliar injury was only observed at pH's between 3.0 and 2.6. Cultivar responses varied indicating that, for yield or growth effects, plant response is not only species-dependent but also strongly cultivar- dependent.

Abouguendia et al. (1986) conducted similar controlled growth experiments with six Saskatchewan forest and crop species and showed that simulated acid rain with pH 3.6 or higher had minimal effects on the crop and forest species studied.

Laboratory studies to determine the effects of simulated acid rain on tree growth have produced conflicting results. Visible injury is often considered the primary indication of dose response or impact. A review of the species studied to date shows that the upper pH limit for injury is about 3.0 for both conifers and deciduous species (RMCC 1986). With the annual average pH of rain in the forested areas of eastern Canada currently above 4.0, there is limited likelihood for direct foliar injury at this time. However, more research is needed in this area using field-grown material to ensure that these assumptions are correct and that there are no extenuating factors.

Atmospheric pollutants may, however, directly affect reproductive processes. Cox (1983) demonstrated that pollen is significantly affected by pH's below 5.6. Furthermore, the pH where a 50% probability of death occurred for all pollen tested was within the range of rainfall acidity in eastern Canada. These results show that the natural regeneration of Canadian forests is at risk.

Cox (1985) tested 11 Canadian forest flora species for the combined effects of copper, lead or zinc and pH on pollen function. The results indicated that, at current copper deposition levels, only the more sensitive species such as sugar maple and yellow birch experienced any effects on pollen germination or tube growth.

Another area of concern is the potential toxic effects of increased aluminum concentrations on tree roots. The possibility that aluminum toxicity is responsible for the dieback currently occurring in eastern North America cannot be ignored. Hutchinson et al. (1986), conducted a study to determine the relative sensitivity of five economically important eastern coniferous species to aluminum. The growth of red and white spruce was somewhat inhibited at 5 mg Al/l and severely inhibited at concentrations greater than 20 mg/l. The growth of the black spruce seedlings was also severely inhibited at concentrations between 20 mg and 150 mg Al/l. In contrast, growth of white pine was actually stimulated by concentrations between 5 and 20 mg Al/l. It was consistently more tolerant to aluminum toxicity than the other four species. Jack pine was intermediate in its response.

Laboratory studies have resulted in an increased understanding of many of the direct effects of acid rain but the importance of these effects still needs to be established for individual species and regions.

3.2.3 Exclusion Canopy Studies

At the Brampton Laboratory of the Ontario Ministry of the Environment, an exclusion canopy system has been used to assess the impact of acid deposition and associated air pollutants on commerically-important crop and tree species (Kuja et al. 1986b).

The system was used to study the effects of simulated acid rain treatments on soybean (cv Hodgson) as measured by seed yield (kg/ha) or components of seed yield. The results did not show any significant yield reduction due to increased acidity of simulated acid rain (Kuja 1988). However, additional research is needed to assess the synergistic effects of acid rain and other pollutants, specifically ozone.

In 1987, a multi-year study was initiated to investigate the potential effects of simulated acid rain, ozone and soil nutrient status on sugar maple (Acer saccharum) and spruce seedlings grown on the rain exclusion canopy treatment plots.

The results from this experiment should provide insight into the possibility that acid rain is having a major detrimental effect on sugar maples in eastern Canada.

3.3 Forest Decline Studies

The central hypothesis in forest decline is that stress of either biotic or abiotic origin alters tree health and renders forests susceptible to further loss of vigor (Manion 1981). Disease organisms ultimately attack the weakened trees and result in their further demise (Houston 1981).

For several years, maple syrup producers in Quebec have been concerned by the apparent decline in the condition of an increasing number of

sugar bushes (Carrier 1986). Maple decline is not a new problem for the province. Lachance (1985), in his summary of historical maple decline in Quebec, documented a seasonal and localized decline in the maple bushes of Beauce County in 1934. This is the same area where the current decline was documented for the first time in 1978.

During the summer of 1982, several cases of sugar maple decline were reported in the province of Quebec. As a result, during the summers of 1983, 1984 and 1985, surveys were conducted in order to determine the scope and severity of the maple decline problem in the province. By 1985, surveys that covered a total area of 25,100 km^2 showed that close to 60 percent of the trees could be classified as 'healthy', or 'slightly affected', 35.4 percent as 'lightly affected', 4.2 percent as 'moderately affected' and 0.9 percent as 'heavily affected' (Carrier 1986). The decline symptoms varied but included earlier fall colouring of small leaves, branch dieback, bark loss from main branches, longer healing time for trunk tap holes, reduced radial increment growth and tree death. In addition, virtually all maple plots showed increased incidence of decline between 1983 and 1985. Average annual tree increment in maple forest association stands decreased between 1981 and 1985.

Results from a comparison of data from 129 sample plots established in the summers of 1983 and 1984 (Gagnon et al. 1985) showed that maple decline was most severe on the wettest (37%) or the driest sites (23%). Also, maple woods containing basswood had a lower severity of decline. Soils were analyzed from the various sites and their pH ranged from 4.0 to 4.7. The area of most severe sugar maple dieback coincided with the occurrence of high levels of nickel, chromium and cobalt in the soil and with magnesium-rich till. Soil potassium deficiencies were also noted in some areas of decline.

Gagnon et al. (1986) detected a decrease in several nutrients over a period of 15 years in soil compositions from 53 maple stands and Bernier et al. (1985) in a study of foliage of Appalachian maple stands

showed that average concentrations of nitrogen and phosphorus were low and those of potassium and calcium were very low. Both the soil and foliar analyses indicate that the nutritional cycle of these maple stands has been disrupted and that these nutritional stress factors have been operating for several years. As a result, several researchers have been conducting fertilization experiments based on soil and foliar analyses for the identification of nutrient deficiencies.

Hypotheses postulated for the decline include insect infestations and climate changes but none of them could be identified as the universal causative factor. Recently, acid precipitation and air pollution have been suggested as the most likely causes since the affected region receives a high annual wet sulphate loading of 40 kg ha^{-1} yr^{-1}.

In Ontario, several maple syrup producers in the Muskoka area expressed concern in 1984 about the apparent increase in dieback and mortality of sugar maple trees in the previous six years. This area has received 30 to 45 kg SO_4 ha^{-1} yr^{-1} over this time period (Dillon et al. 1988) and the lakes in the region are well-known to be affected adversely.

In 1984, permanent observation plots were established in seven maple woodlots in the Muskoka area and in one woodlot near Thunder Bay in north-western Ontario as a control plot. The 1984 results indicated that the current decline outbreak first began in 1978. Symptoms appeared throughout the Muskoka region with no consistent pattern apparent (McLaughlin et al. 1985). When the data from all seven plots were combined, 58% of the trees were considered healthy, 20% were experiencing light to moderate decline symptoms, and 22% were exhibiting severe decline symptoms. Decline symptoms appeared to be most pronounced on older trees and on tapped or wounded trees. Site nutrient deficiencies did not appear to be implicated in the sugar maple decline.

The soil at the Muskoka sites had a mean pH of 4.8, and had high concentrations of exchangeable aluminum, ranging from 6 mg to 40 mg per kg in mineral soil (McLaughlin et al. 1985). Declining trees suffered extensive root death with significantly higher aluminum concentrations in the fine roots. Foliar tissue leaching was apparent with reduced elemental concentrations in the tops of the tree crowns. Annual growth increments were very small in all trees during the forest tent caterpillar defoliations in 1976 and 1977; however, growth recovered in the healthy trees after the collapse of the epidemic but not in the declining trees. Furthermore, incremental growth in the declining trees appeared to be decreasing 20 years prior to the epidemic.

Although the prime factors for this decline probably include the severe insect infestations in 1976 and 1977, and the spring droughts in 1976, 1977 and 1983, acid precipitation is an additional environmental stress on the maple bushes in the Muskoka area (McLaughlin et al. 1985).

Forest declines are also occurring in the Maritime provinces. In 1985, in the course of general surveillance, unexplained white spruce decline was observed in northern New Brunswick (Canadian Forestry Service 1986). The condition involved areas of several hundred hectares in Restigouche County with the greatest decline apparent in mature trees but some effects also evident on other age-classes. In addition, red spruce deterioration was observed in the southern part of the province. Although spruce budworm infestations were responsible for defoliation in the past, they do not adequately explain the conditions observed. Both of these problems are being investigated further.

Since 1979, early leaf browning and premature leaf fall have been occurring annually in white birch in southern New Brunswick and occasionally in Nova Scotia in western Cumberland County along the Bay of Fundy (Canadian Forestry Service 1986). Although mainly a condition of white birch, similar symptoms were observed in 1980 and 1981 on other deciduous species. The condition appears to be limited to a coastal strip of 1-15 km in width which extends inland about 30 km,

mainly in low-lying areas. In 1985, detailed weekly observations were made in an attempt to determine the problem's cause. Although it was determined that several organisms were associated with this condition, none of them, alone or in combination, could satisfactorily explain the situation. This area is frequently subjected to acid fog episodes and intensive monitoring of air pollutants in coastal fog is now in progress.

Currently, the relative importance of acid deposition and air pollution stress in relation to other stresses such as diseases, insects, weather extremes and climate, still needs to be clarified for the major eastern Canadian declines. However, it is likely that the added stress of air pollution has increased the trees' susceptibility to other stresses.

3.4 Wildlife Effects

3.4.1 Amphibians

A number of field and laboratory studies have been undertaken to assess the actual and potential effects of acid deposition on amphibian distribution and abundance.

Surveys of amphibian breeding habitats in Canada in areas unaffected by local sources have shown that many of these habitats are very acidic (Pough 1976; Dale et al. 1985; Gascon and Planas 1986).

Poor reproductive success has been documented as resulting in smaller populations in very acidic environments. Increased embryonic mortality at low pH (pH <5.0) has been measured in both natural populations and *in situ* bioassays (Saber and Dunson 1978; Clark and Hall 1985; Clark 1986; Freda and Dunson 1986). Elevated aluminum concentrations in acidic natural waters are also toxic and can further reduce embryonic survival (Clark and LaZerte 1985; Clark and Hall 1985; Glooschenko et al. 1985).

Even though amphibian larvae are more acid-tolerant than embryos they are more vulnerable to indirect effects of acidification due to potentially limited food resources. Because they are feeding very actively during the larval stage, food resources and competitive relationships are very important.

The food resource for the larval stage consists of benthic invertebrates and plankton whose community structure and species composition can be altered at pH <5.6 (Mierle et al. 1986).

3.4.2 Waterfowl

Because of their dependence on the aquatic environment for nest sites, brood protection and food, the loss or degradation of this environment by acidification could have serious implications for the future of the waterfowl resource in eastern Canada. The severity of such effects will depend on the sensitivity of the nesting habitats.

McNicol et al. (1985) conducted comparisons of waterfowl breeding success in central and northern Ontario and showed that productivity was significantly lower in the headwater lakes receiving deposition greater than 30 kg of SO_4 ha^{-1} yr^{-1}. Also, breeding success rates were affected by the abundance of fish stocks and the fish community structure.

The diets of some fish and ducks overlap in simple headwater lake systems. With the critical life-stage for food availability being the early brood development period, survival can also be affected by competition with fish for available aquatic insect prey, especially since the community and population structure of benthic invertebrates can be altered at pH <5.6 (Mierle et al. 1986).

4.0 AQUATIC/CATCHMENT STUDIES

The effects of acidic deposition on aquatic systems in Canada have been described and reviewed in detail in three major reports: Harvey et al. (1981), Environment Canada (1983) and RMCC (1986). In addition, Canadian information has been included in reviews prepared by American agencies including National Academy of Sciences (1986), Environmental Protection Agency (1985), and Cook (1988) and in technical review articles (e.g. Dillon 1983; Dillon et al. 1984; Haines 1981). The information presented in these reports is not repeated here; instead, a summary is provided highlighting more recent findings.

4.1 Chemical Studies

4.1.1 Surveys - Extent of Sensitivity/Damage

There are an estimated 700,000 lakes in Canada below 52°N east of the Ontario-Manitoba border, which corresponds approximately to the zone where SO_4 deposition is greater than approximately 1 g (wet) SO_4 m^{-2} yr^{-1} (Kelso et al. 1986).

Based on chemical surveys done in each province, Minns & Kelso (1986) and Kelso et al. (1986) estimated that 50% of these lakes had alkalinity <50 µeq L^{-1}, a level that indicates sensitivity to acid deposition.

Furthermore, an estimated 20% (∿150,000) lakes had pH ≤6.0, indicating that biological effects may have occurred, while ∿14,000 lakes were estimated to have pH <4.7, a level at which biological effects are expected to be very severe (Mills and Schindler 1986; Mierle et al. 1986). Although the proportion of these lakes with pH <6.0 that are dystrophic (high concentrations of dissolved organic acids) is not known, it is highly unlikely that the low pH's can be explained by this factor (see below),

except possibly for the Maritime provinces. Minns and Kelso also predicted, based on a simple model derived from the Henriksen (1979, 1982) and Wright (1983) relationships, that ∿9% of these 700,000 lakes would ultimately have pH <5.0 if 'current' (1980) SO_4 deposition remained constant. However, the model is not validated, nor is the 'constant deposition' assumption valid; SO_4 deposition has dropped in at least part of eastern Canada since 1980 (see Section 4.2.2 and Dillon et al. 1988).

The sensitivity and extent of effects on lakes in eastern Canada has also been assessed on a regional basis by Jeffries et al. (1988) and Neary and Dillon (1988). Both of these studies showed that not only was the extent of affected lakes great in eastern Canada and Ontario, respectively, but that organic acids did not play a significant part in the distributions of lake pH or alkalinity. For example, the highest organic acid levels in Ontario were found in the zone containing the lakes with the highest average pH's and alkalinities where S deposition was lowest (Fig. 5). In fact, in Ontario at least, there are no known lakes in zones where S deposition is <0.5 $g/m^2/yr$ that have high DOC and pH <6.0.

Both the Ontario and the eastern Canadian surveys also demonstrated that the pattern of SO_4 concentration in lakes followed the S deposition pattern, a result consistent with the findings of the survey of lakes in the eastern USA (Landers et al. 1988). Neary and Dillon (1988) also found that, in Ontario, there was a strong relationship between both lake alkalinities and pH's and S deposition, provided that only the lakes with conductivity <50 µS were considered. These data provided a strong indication of both widespread reductions in alkalinity and pH and a cause-effect relationship with S deposition.

There are relatively few data available to assess the effects on groundwaters in Canada. Azzaria et al. (1982) reported that in

the Lac Laflamme (Quebec) catchment, shallow groundwater in zones of rapid infiltration had pH <4.5, while Craig et al. (1986) and Johnston et al. (1985) and Bottomly et al. (1984) found that shallow groundwater in the Turkey Lakes watershed (Ontario) demonstrated pH decreases (from ∿5.2 to 4.6) in response to precipitation events.

4.1.2 Trends in Lakes and Streams

In Canada, as elsewhere, there is a paucity of historical water quality data useful for determining both the extent and rate of acidification of surface waters. As mentioned earlier, until the late 1970's acid deposition was considered to be a local (e.g. Sudbury, Wawa, Trail) rather than a regional problem with effects apparent only in areas adjacent to major SO_2 sources. With very few exceptions, detailed monitoring programmes designed to measure directly acidification rates and to monitor chemical trends were not established until the 1980's. As a result, assessment of the chemical trends in acidification has relied largely on indirect evidence, e.g. paleolimnological relationships, geochemical relationships, or comparison of old and new data collected a number of years apart. The latter approach is usually compromised by changes in analytical methods.

The only reported examples of direct continuous measurement of lakes in high S deposition zones are Plastic and Harp Lakes in Ontario (Dillon et al. 1987). Plastic Lake's alkalinity declined by 2.1 ± 0.4 µeq L^{-1} yr^{-1} between 1979 and 1985, while its pH dropped 0.035 ± 0.007 units yr^{-1} (Fig. 6); Harp Lake, on the other hand demonstrated no significant change in either pH or alkalinity. The difference between these lakes was attributed to the fact that the Plastic Lake catchment is covered by very thin (<1 m) sandy basal till with many exposed bedrock (orthogneiss) ridges, while the Harp Lake catchment is covered by a generally

thicker overburden of glacial till >1 m deep on ∿50% of the catchment and ∿10 m thick in the valley bottoms. Thus, Plastic Lake was typified as a 'sensitive' lake while Harp Lake was considered to be relatively insensitive.

The loss of alkalinity in Plastic Lake was offset by a decrease in base cations, principally Ca, Na and K, but not an increase in strong acid anions (SO_4^{2-}, NO_3^-), indicating that depletion of available cations may have occurred in the catchment. The situation was complicated by the fact that over the period of study S deposition was decreasing. Unlike Plastic Lake, the Harp Lake SO_4^{2-} concentration decreased as a result of the declining S deposition.

Other sites with long term records, especially Rawson Lake and other ELA lakes (Schindler 1988) exist, but these are situated in a region where S deposition is low, and changes in lake chemistry are not expected.

Although a number of paleolimnological studies based on either diatom or chrysophyte -pH relationships have been conducted in areas where local sources have acidified lakes (e.g. Dickman 1985; Dixit 1986), there is little information yet available for any sensitive lakes in the rest of eastern Canada. The PIRLA project (Charles et al. 1986) includes three lakes in Algonquin Park, Ontario, but none have pH <6.0. Griffiths et al. (1988) have produced a calibration for Ontario lakes based on a large sample size (∿60 lakes), and work is in progress to test this on a number of lakes including Plastic Lake.

4.2 Catchment Studies

Much of the acid rain research in Canada has concentrated on the effects of acid deposition on whole catchments, i.e. on both the aquatic and terrestrial portions of catchments. A summary of the major catchment studies currently in progress in eastern Canada is given in Table 3; their locations are shown in Figure 7.

In each of these studies, hydrologic and elemental fluxes are measured in one or more catchments and lakes. These catchment studies also include soil and vegetation measurements and some tree condition and regeneration studies.

The sensitivity of the sites varies. The Experimental Lakes Area in northwestern Ontario has shallow podzolic basal tills with extensive bedrock exposure on hillcrests, but deep soils in low areas. Some of these sites are of moderate sensitivity to acidification, while others are very sensitive.

The Turkey Lakes basin is located on the Precambrian Shield but is only moderately sensitive since the till is of variable thickness and contains a small amount of calcium carbonate (1 to 2%).

The catchments being studied by the Dorset Research Centre are located on the Precambrian Shield with overburden consisting mostly of thin till and rock ridges. The soils at Plastic Lake watershed are generally thin, acidic, weakly developed podzols. Most of these catchments are extremely sensitive as a result.

The Lac Laflamme catchment, within the Montmorency Experimental Forest, also lies on the Precambrian Shield and is extremely sensitive as well.

The poorly buffered oligotrophic watersheds combined with the low bicarbonate buffering capacity of the lakewaters also make the Kejimkujik catchments extremely sensitive to acidification.

These whole catchment studies provide valuable data on the interaction between terrestrial and aquatic systems.

4.3 Biological Effects

Most of the early concern relating to biological effects focussed on fish, particularly sports fisheries. The decline of the Atlantic salmon fishery in a number of Nova Scotia rivers with low pH is well-documented (Watt et al. 1983) and supported by laboratory (Peterson 1984) and field (Lacroix 1985) studies. Adverse effects on several fish populations in Ontario were documented by Harvey (1982), while Beggs and Gunn (1986) showed regional effects on lake trout and brook trout populations in Ontario.

More recently, evidence has accumulated from both field and laboratory studies that other organisms lower in the food web (including cyprinids, molluscs, crustaceans) are affected at higher pH's than many of the sports fish species (Schindler et al. 1985; Mills and Schindler 1986; Holtze et al. 1988). Because these lower trophic level organisms are usually the major food resource of the 'sports' fish, their disappearance or reduction in abundance at higher pH's may have a major effect on the fish populations. In other words, the principal effects on fish are more likely to be indirect rather than acute toxicological response to pH (or aluminum).

Much of the information relating to the biological effects of acidic deposition in Canada is derived from the experimentally acidified lakes (L.223, L.302) in the Experimental Lakes Area (Schindler et al. 1985; see Can. J. Fish. Aquat. Res., 37, March, 1980 and Can. J. Fish. Aquat. Res., 44, Supplement 1, 1987).

Acidification of L.223 from pH 6.8 to 5.0 over an 8-yr period resulted in changes to many components of the food web (Table 2; Mills and Schindler 1986). Diversity of most algae, zooplankton, benthos and fish declined, while some species were lost and others appeared for the first time. Significant changes began at a pH just below 6.0, e.g. decline in Mysis relicta (Nero and Schindler 1983), and decline in fathead minnow populations. The appearance of filamentous algae (Mougeotia spp.) occurred at pH of 5.6, consistent with the observations of Jackson (1985) who surveyed 40 lakes in Ontario. Lake trout recruitment failure at pH ∿5.6 and white sucker recruitment failure at 5.0 were consistent with results of laboratory studies (N. J. Hutchinson et al. 1988). Recruitment failure of the crayfish Orconectes virilis in L.223 at pH ∿5.6 was similar to the results of laboratory and field toxicity tests (Berrill et al. 1985) with two other species of Orconectes.

As Plastic Lake has acidified (Dillon et al. 1987), a variety of biological effects have been observed and attributed to its declining pH. Harvey and Lee (1982) observed a dead and dying pumpkinseed sunfish population in the littoral zone of the lake each spring. Stephenson and Mackie (1986) found a depauperate population of Hyalella azteca, a common and normally very abundant amphipod, in Plastic Lake in 1983. In the following year no recruitment was observed, and the population subsequently disappeared. The population of a common and usually abundant snail, Amnicola limnosa, had reduced growth rate and abundance in 1980 (Rooke and Mackie 1984, 1984a and 1984b), and is probably now extinct. Many other effects common to acidic lakes have been observed (blooms of filamentous algae, reduced zooplankton richness, loss of zooplankton species, loss of crayfish), but as yet they are unpublished.

There are very few data available allowing assessment of the effects of acidic deposition on stream biota. Hall and Ide (1987) showed that several mayfly and stonefly species disappeared between 1937-42 and 1984-85 from several streams in Algonquin Park, Ontario that

demonstrated pH decreases of >1 unit during snowmelt. Neighbouring streams that showed no pH decline had not lost the same benthic invertebrate species.

Although only a few case studies provide direct documentation of biological effects in Canada, the results of these few studies are consistent with both laboratory toxicology studies and with the whole-ecosystem experiments at the Experimental Lakes Area.

5.0 SUMMARY

Acid rain research conducted by Canadian federal and provincial agencies since the late 1970's have contributed immensely to our overall understanding of the acid rain problem.

Atmospheric studies have shown that the southern portions of the provinces of Ontario and Quebec receive the highest deposition rates of strong acid, that there are seasonal and episodic trends to sulphate deposition, that fogs and low clouds have high concentrations of strong acid anions and extremely low pH's, and that atmospheric models can be used to simulate deposition.

The terrestrial studies have shown that acid deposition can affect tree growth and regeneration by a combination of factors including loss of nutrients, Al toxicity and direct effects on reproductive processes. The added stress of air pollution can increase the trees' susceptibility to other stresses (insects, disease, weather).

The aquatic studies have documented the acidification of a sensitive lake (Plastic Lake in Ontario) and observed a variety of biological effects as a result of the declining pH. Surveys in Ontario and other parts of eastern Canada have demonstrated that the pattern of SO_4 concentration in lakes follows the S deposition pattern. There is widespread reduction in alkalinity and pH as a result of S deposition.

These data continue to support the Canadian federal/provincial decision which has resulted in regulations to reduce SO_2 emissions by 50% by 1994.

REFERENCES

Anon. 1941. Trail smelter arbitral tribunal decision. Amer. J. Int. Law: 684-737.

Abouguendia, Z.M. L.A. Baschak and R.C. Goodwin. 1986. Effects of simulated acidic precipitation on Saskatchewan crop and forest species-results of the 1985/86 experiments. SRC Technical Report No. 191.

Azzaria, L.M., P.J. Gelinas, R. Robitaille and J.F. Wilhelmy. 1982. Etude géologique et hydrogéologique du lac Laflamme, Parc des Laurentides, Québec. Report for Environment Cnada, Inland Waters Directorate, Dept. of Geology, U. of Laval, Ste. Foy, Québec, 95 p.

Bailey, C. and D.W. Larson. 1982. Water quality and pH effects on *Umbilicaria nammulata* (Ach.) Tuck. Bryologist. 85: 431.

Barrie, L.A. and A. Sirois. 1986. Wet and dry deposition of sulphates and nitrates in eastern Canada: 1979-1982. Wat. Air Soil Pollut. 30: 303-310.

Beamish, R.J. 1974a. The loss of fish populations from unexploited remote lakes in Ontario, Canada as a consequence of atmospheric fallout of acid. Water Res. 8: 85-95.

Beamish, R.J. 1974b. Growth and survival of white suckers (*Catostomus commersoni*) in an acidified lake. J. Fish. Res. Board Can. 31: 49-54.

Beamish, R.J. and H.H. Harvey. 1972. Acidification of the La Cloche Mountain Lakes, Ontario, and resulting fish mortalities. J. Fish. Res. Board Can. 29: 1131-1143.

Beamish, R.J., W.L. Lockhart, J.C. Van Loon and H.H. Harvey. 1975. Long-term acidification of a lake and resulting effects on fishes. Ambio 4: 98-102.

Beggs, G.L. and J. M. Gunn. 1986. Response of lake trout (Salvelinus namaycush) and brook trout (S. fontinalis) to surface water acidification in Ontario. Wat. Air Soil Pollut. 30: 711-717.

Bernier, B., M. Brazeau, C. Camire and A. Brousseau. 1985. Recherche sur le dépérissement et le status nutritif de l´érablière des Appalaches au Québec. Rapport d´étape sur les travaux réalisésen 1984-1985: 62 pp.

Berrill M., L. Hollett, A. Margosian and J. Hudson. 1985. Variation in tolerance to low environmental pH by the crayfish Orconectes rusticus, O. propinquis, and Cambarus robustus. Can. J. Zool. 63: 2586-2589.

Bottomly, D.J., D. Craig and L.M. Johnston. 1984. Neutralization of acid runoff by groundwater discharge to streams in Canadian Precambrian Shield watersheds. J. Hydrol. 75: 1-26.

Canadian Forestry Service. 1986. Forest Insect and Disease Conditions in Canada 1985. ISBN 0-662-14890: 107 pp.

Canada/U.S. Memorandum of intent between the government of Canada and the government of the United States of America concerning transboundary air pollution. 1980.

Carrier, L. 1986. Decline in Québec's forests: assessment of the situation. ISBN 2-550-16816-X. Dépôt légal, Bibliothèque nationale du Québec.

Case, J.W. 1985. Mapping trace element deposition in Ontario using lichens and mosses as biological monitors. Poster Presentation

at International Symposium on Acidic Precipitation, Muskoka '85 Conference, Muskoka, Canada.

Charles, D.F. et al. 1986. The PIRLA Project (Paleoecological Investigation of Recent Lake Acidification): Preliminary Results for the Adirondacks, New England, N. Great Lakes States, and N. Florida. Wat. Air Soil Pollut. 30: 355-365.

Clark, K.L. and B.D. LaZerte. 1985. A laboratory study of the effects of aluminum and pH on amphibian eggs and tadpoles. Can. J. Fish. Aquat. Sci. 42: 1544-1551.

Clark, K.L. and R.J. Hall. 1985. Effects of pH and aluminum on amphibian embryo-larval survival. Can. J. Zool. 63: 116-123.

Clark, K. L. 1986. Distributions of anuran populations in central Ontario relative to habitat acidity. Wat. Air Soil Pollut. 30: 727-734.

Cook, R.B. (editor). 1988. The effects of acidic deposition on aquatic resources in Canada: An analysis of past, present, and future effects. ORNL/TM-10405.

Cox, R.M. 1985. Determination of the sensitivity of forest flora reproductive processes to wet deposited trace elements and acid due to long range transported air pollutants. Canadian Forestry Service Contract Report No. OS082-00289: 160 pp.

Cox, R.M. 1983. Sensitivity of forest plant reproduction to long range transported air pollutants: In vitro sensitivity of pollen to simulated acid rain. New Phytol. 95: 269-276.

Craig, D., L.M. Johnston and D.J. Bottomley. 1986. Acidification of shallow groundwaters due to acid shock events. Manuscript

Report, National Hydrology Res. Inst., Env. Canada, Ottawa, Canada, 16 p.

Dale, J., B. Freedman and J.J. Kerekes. 1985. Acidity and associated water chemistry of amphibian habitats in Nova Scotia. Can. J. Zool. 63: 97-105.

Den Hartog, G., H.H. Neumann and K.M. King. 1987. Measurements of ozone, sulphur dioxide and carbon dioxide fluxes to a deciduous forest. Reprinted from the Proceedings of the 18th Conference on Agricultural and Forest Meteorology and 8th Conference on Biometeorology and Aerobiology, September 14-18, 1987.

Dickman, M.D. and H.G. Thode. 1985. The rate of lake acidification in four lakes north of Lake Superior and its relationship to downcore sulphur isotope ratios. Wat. Air Soil Pollut. 26: 233-253.

Dillon, P.J. 1983. Chemical alterations of surface waters by acidic deposition in Canada. Wat. Qual. Bull. 8: 127-132.

Dillon, P.J., D.S. Jeffries, and W.A. Scheider. 1982. The use of calibrated lakes and watersheds for estimating point source. Wat. Air Soil Pollut. 18: 241-258.

Dillon, P.J., D.S. Jeffries, W. Snyder, R. Reid. N.D. Yan, D. Evans, J. Moss, and W.A. Scheider. 1978. Acidic precipitation in south-central Ontario. J. Fish. Res. Board Can. 35: 809-815.

Dillon, P.J., M. Lusis, R. Reid and D. Yap. 1988. Ten-year trends in sulphate and nitrate deposition in central Ontario. Atmos. Environ. 22: 901-905.

Dillon, P.J., N.D. Yan and H.H. Harvey. 1984. Acidic precipitation: effects on aquatic ecosystems. CRC Critical Reviews in Environmental Control 13: 167-194.

Dillon, P.J., R.A. Reid and E. de Grosbois. 1987. The rate of acidification of aquatic ecosystems in Ontario, Canada. Nature. 329: 45-48.

Dixit, Sushil S. 1986. Diatom-inferred pH calibration of lakes near Wawa, Ontario. Can. J. Bot. 64: 1129-1133.

Edwards, G.C. and G.L. Ogram. 1986. Eddy correlation measurements of dry deposition fluxes using a tunable diode laser absorption spectrometer gas monitor. Wat. Air Soil Pollut. 30: 187-194.

Ellenton, G., P.K. Misra and B. Ley. 1988. The relative roles of emissions changes and meteorological variability in variation of wet sulphur deposition: a trajectory model study. Atmos. Environ. 22: 547-556.

Ellenton, G., B. Ley and P.K. Misra. 1985. A trajectory puff model of sulphur transport for eastern North America. Atmos. Environ. 19: 727-737.

Environment Canada. 1983. Canada-United States, Memorandum of Intent on Transboundary Air Pollutants, Impact Assessment Final Report.

Environmental Protection Agency. 1985. The acidic deposition phenomenon and its effects. Critical Assessment Document. EPA/600/8-85/001.

Enyedi, A.J. and A.L. Kuja. 1986. Assessment of relative sensitivities during early growth stages of selected crop species subjected to simulated acidic rain. Wat. Air Soil Pollut. 31: 325-335.

Freda J. and W.A. Dunson. 1986. Effects of low pH and other chemical variables on the total distribution of amphibians. Copeia: 454-466.

Gagnon, G., G. Roy, C. Gravel and J. Gagné. 1986. Etat des recherches sur le dépérissement au ministère de l´Energie et des Ressources. Journée d´information sur l´acériculture: 47-85.

Gagnon, G., L. Robitaille, G.Roy and C. Gravel. 1985. Le dépérissement des érablières: comportement de certaines variables écologiques. La terre de Chez Nous (dossier). 3: 28 pp.

Gascon, C. and D. Planas. 1986. Spring pond water chemistry and the reproduction of the wood frog, Rana sylvatica. Can. J. Zool. 64: 543-550.

Glooschenko, V., W. Weller and C. Eastwood. 1985. Amphibian abundance and distribution with respect to environmental contaminants and pH stress adjacent to Sudbury, Ontario. Technical report of Wildlife Branch, Ontario Ministry of Natural Resources, Queen's Park, Toronto. 30 pp.

Griffiths, R.W., E. Carney, L. Nakamoto and K.H. Nicholls. 1988. Parameterization of calibration equations relating diatom microfossils to surface water pH and alkalinity in central Ontario lakes. Submitted to Ecological Monograph.

Haines, T.A. 1981. Acidic Precipitation and its consequences for aquatic ecosystems: A review. Transactions of the American Fisheries Society. 110: 669-707.

Hall, R.J. and F.P. Ide. 1987. Evidence of acidification effects on stream insect communities in central Ontario between 1937 and 1985. Can. J. Fish. Aquat. Sci. 44: 1652-1657.

Harvey, H.H., R.C. Pierce, P.J. Dillon, J.P. Kramer, and D.M. Whelpdale. 1981. Acidification in the Canadian Aquatic Environment. Publ. NRCC No. 18475 of the Environmental Secretariat, National Research Council, Canada.

Harvey, H.H. 1982. Population responses of fish in acidified waters. In Johnson, R.E. (ed.), Acid Rain/Fisheries: Proceedings of an International Symposium on Acidic Precipitation and Fishery Impacts in Northeastern North America, American Fisheries Society, Bethesda, MD.

Harvey, H.H. and C. Lee. 1982. Historical fisheries changes related to surface water pH changes in Canada. Acid Rain/Fisheries. Proceedings of an International Symposium on Acidic Rain and Fishery Impacts in Northeastern North America, Cornell University, Ithaca, New York.

Hedin, L.O., Likens, G.E. and F.H. Bormann. 1987. Decrease in precipitation acidity resulting from decreased sulphate concentration. Nature 325: 244-246.

Henriksen, A. 1979. A simple approach for identifying and measuring acidification of freshwater. Nature 278: 542-545.

Henriksen, A. 1982. Preacidification pH - values in Norwegian rivers and lakes. NIVA Report 3/1982.

Holtze, K.E., N.J. Hutchinson, J.R. Munro and T.W. Pawson. 1988. Lethality of H^+ and Al to early life stages of six fish species inhabiting PreCambrian Shield waters of Ontario. Submitted to Can. J. Fish. Aquat. Sci.

Houston, D.R. 1981. Stress-triggered tree disease: the diebacks and declines. NF-INF-41-81. United States Department of Agriculture, Forest Service, Broomall, Pennsylvania, USA.

Hutchinson, N.J., K.E. Holtze, J.R. Munro and T.W. Pawson. 1988. Modifying effects of life stage, ionic strength and post-exposure mortality on lethality of H^+ and Al to lake trout and brook trout. Aquat. Toxic. in press.

Hutchinson, T. and M. Scott. 1986. Effects of long-term simulated acid precipitation on forest ecosystems: The Burt Lake and maple decline in Ontario projects. Presented at the Forest Decline Workshop, Oct. 20-22, 1986.

Hutchinson, T.C. 1980. Effects of acid leaching on cation loss from soils. In T.C. Hutchinson and M. Hava (eds). Effects of acid precipitation on terrestrial ecosystems. NATO Conf. Series, Plenum Press, New York.

Hutchinson, T., L. Bozic and G. Munoz-Vega. 1986. Responses of five species of conifer seedlings to aluminum stress. Wat. Air Soil Pollut. 31: 283-294.

Jackson, M. 1985. Filamentous algae in Ontario softwater lakes. Poster presentation at Internat. Symp. on Acidic Precipitation, Sept. 15-20, 1985, Muskoka, Canada.

Jeffries, D.S., R.G. Semkin, R. Neureuther, and M. Seymour. 1986. Influence of atmospheric deposition on lake mass balances in the Turkey Lakes Waterhed, Central Ontario. Wat. Air Soil Pollut. 30: 1033-1044.

Jeffries, D.S., D. Wales, J.R.M. Kelso and R.A. Linthurst. Regional chemical characteristics of lakes in North America: Part I - eastern Canada. Wat. Air Soil Pollut. 31: 551-567.

Johnston, L.M., D.J. Bottomley, D. Craig, K. Inch and H. Chew. 1985. The role of groundwater in modifying the effects of acidic

precipitation on surface waters. Manuscript Report, National Hydrology Res. Inst., Env. Canada, Ottawa, Canada.

Jones, H.G. and C. Deblois. 1987. Chemical dynamics of N- containing ionic species in a boreal forest snowcover during the springmelt period. Hydrol. Proc. 1: 271-282.

Kelso, J.R.M., C.K. Minns, J.E. Gray and M.L. Jones. 1986. Acidification of surface waters in eastern Canada and its relationship to aquatic biota. Can. Spec. Publ. Fish. Aquat. Sci., 87, 42 pp.

Kerekes, J. and B. Freedman. 1986. Physical, chemical, and biological characteristics of three watersheds in Kejimkujik National Park, Nova Scotia. Env. Can. Report.

Kerekes, J., G. Howell, S. Beauchamp, and T. Pollock. 1982. Characterization of three lake basins sensitive to acid precipitation in central Nova Scotia (June 1979 to May 1980). Int. Revue. ges. Hydrobiol. 67: 679-694.

Kuja, A. 1988. A Canadian evaluation of NAPAP's interim assessment of the effects of acidic deposition on agricultural crops. Presented at the APCA Conference in January 1988.

Kuja, A., R. Jones and A. Enyedi. 1986. A mobile rain exclusion canopy system to determine dose-response relationships for crops and forest species. Wat. Air Soil Pollut. 31: 307-315.

Kurtz, J., A.J.S. Tang, R.W. Kirk and W.H. Chan. 1984. Analysis of an acid rain deposition episode at Dorset, Ontario. Atmos. Environ. 18: 387-394.

Lachance, D. 1985. Répartition géographique et intensité du dépérissement de l'érable à sucre dans les érablières au Québec. Phyto-protection 66: 83-90.

Lacroix, G.L. 1985. Survival of eggs and alevins of Atlantic salmon (Salmo salar) in relation to the chemistry of interstitial water in redds in some acidic streams of Atlantic Canada. Can. J. Fish. Aquat. Sci. 42: 292-299.

Landers, D.H., W.S. Overton, R.A. Linthurst and D.F. Brakke. 1988. Eastern lake survey. Envir. Sci. Technol. 22: 128-135.

LaZerte, B.D. and P.J. Dillon. 1984. Relative importance of anthropogenic versus natural sources of acidity in lakes and streams of central Ontario. Can. J. Fish. Aquat. Sci. 41: 1664-1677.

Leaitch, W.R., J.W. Strapp, H.A. Wiebe and G.A. Isaac. 1986. Chemical and microphysical studies of non-precipitating and precipitating cloud. J. of Geophysical Research 91 (D11): 11821-11831.

Lewis, Drew and Davis, William. 1986. Joint report of the special envoys on acid rain. 35 pp.

Linzon, S.N. and P.J. Temple. 1980. Soil resampling and pH measurements after an 18-year period in Ontario. Proc. In Conf. on the Ecological Impact of Acid Precipitation, Sandefjord, Norway: 176-177.

Lusis, M.A., A.J.S. Tang, W.H. Chan, D. Yap, J. Kurtz and P.K. Misra. 1986. Sudbury smelter impact on atmospheric deposition of acidic substances in Ontario. Wat. Air Soil Pollut. 30: 897-908.

Manion, P.D. 1981. Tree disease concepts. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, U.S.A.

McLaughlin, D.L., S.N. Linzon, D.E. Dimma and W.D. McIlveen. 1985. Sugar maple decline in Ontario. Report No. ARB-144-85-Phyto, Ontario Ministry of the Environment, Toronto, Canada: 18 pp.

McNicol, D.K., B.E. Bendell and R.K. Ross. 1985. Waterfowl and aquatic ecosystem acidification in northern Ontario. Manuscript report, Canadian Wildlife Service, Env. Canada, Ottawa, Canada.

Mierle, G., K. Clark and R. France. 1986. The impact of acidification on aquatic biota in North America: A comparison of field and laboratory results. Wat. Air Soil Pollut. 31: 593-604.

Mills, K.H. and D.W. Schindler. 1986. Biological indicators of lake acidification. Wat. Air Soil Pollut. 30: 779-789.

Minns, Charles K. and John R.M. Kelso. Estimates of existing and potential impact of acidification on the freshwater resources of eastern Canada. Wat. Air Soil Pollut. 31: 1079-1090.

Morrison, I.K. 1981. Effect of simulated acid precipitation on composition of percolate from reconstructed profiles of two northern Ontario forest soils. Can. For. Serv. Res. Notes 1: 6-8.

National Academy of Sciences. Committee on Monitoring and Assessment of Trends in Acid Deposition. 1986. Acid deposition long-term trends. National Academy Press, Washington, D.C.

Neary, B.P. and P.J. Dillon. 1988. Effects of sulphur deposition on lake water chemistry in Ontario. Nature. 333: 340-343.

Nero, R.W. and D.W. Schindler. 1983. Decline of Mysis relicta during acidification of lake 223. Can. J. Fish. Aquat. Sci. 40: 1905-1911.

Ogram, G.L., F.J. Northrup and G.C. Edwards. 1988. Fast-time response - tunable diode laser measurements of atmospheric trace gases for eddy correlation. J. Atmos. Oceanogr. Techn.: in press.

Peterson, R.H. 1984. Influence of varying pH and some inorganic cations on the perivitelline potential of eggs of Atlantic Salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 41: 1066-1069.

Pough, F.H. 1976. Acid precipitation and embryonic mortality of spotted salamanders, *Ambystoma maculatum*. Science 192: 68-70.

Reuss, J.O. and D.W. Johnson. 1985. Effect of soil processes on the acidification of water by acid deposition. J. Environ. Qual. 14: 26-31.

RMCC. 1986. Assessment of the state of knowledge on the long-range transport of air pollutants and acid deposition. Part 2. Atmospheric sciences: 108 pp. Part 3. Aquatic effects: 57 pp. Part 4. Terrestrial effects: 80 pp. Federal/Provincial Research and Monitoring Coordinating Committee (RMCC).

Rooke, J.B. and J.B. Mackie. 1984a. Molluscs of six low-alkalinity lakes in Ontario. Can. J. Fish. Aquat. Sci. 41: 777-782.

Rooke, J.B. and J.B. Mackie. 1984b. Growth and production of three species of molluscs in six low alkalinity lakes in Ontario, Canada. Can. J. Zool. 62: 1474-1478.

Rutherford, G.K., G.W. van Loon, S.F. Mortensen and J.A. Hern. 1985. Chemical and pedogenetic effects of simulated acid precipitation on two eastern Canadian forest soils. II. Metals. Can. J. For. Res. 15: 848-854.

Saber, P.S. and W.A. Dunson. 1978. Toxicity of bog water to embryonic and larval anuran amphibians. J. Exp. Zool. 204: 33-42.

Schemenauer, R. 1986. Acidic deposition to forests. The 1983 chemistry of high elevation fog (CHEF) project. Atmosphere-Ocean 24: 303-328.

Schemenauer, R. and C. Winston. 1988. The 1986 chemistry of high elevation fog project. Presented at the 81st APCA Annual Meeting, June 1988.

Schindler, D.W. 1987. Detecting ecosystem responses to anthropogenic stress. Can J. Fish. Aquat. Sci. 44, Suppl. 1: 6-25.

Schindler, D.W. 1988. Effects of acid rain on freshwater ecosystems. Science 239: 149-157.

Schindler, D.W. and M.A. Turner. 1982. Biological, chemical and physical responses of lakes to experimental acidification. Wat. Air Soil Pollut. 18: 259-271.

Schindler, D.W., K.H. Mills, D.F. Malley, D.L. Findlay, J.A. Shearer, I.J. Davies, M.A. Turner, G.A. Linsey, D.R. Cruikshank. 1985. Long-term ecosystem stress: The effects of years of experimental acidification on a small lake. Science 228: 1395-1401.

Seip, H.M., R. Seip, P.J. Dillon, and E. de Grosbois. 1985. Model of sulphate concentration in a small stream in the Harp Lake catchment, Ontario. Can. J. Fish Aquat. Sci. 42: 927-937.

Semkin, P.G. and D.S. Jeffries. 1986. Bulk deposition of ions in the Turkey Lakes watershed. Water Poll. Res. J. Canada 21: 474-485.

Somers, Keith M. and Harold H. Harvey. 1984. Alteration of fish communities in lakes stressed by acid deposition and heavy metals near Wawa, Ontario. Can. J. Fish. Aquat. Sci. 41: 20-29.

Stephenson, M. and G.L. Mackie. 1986. Lake acidification as a limiting factor in the distribution of the freshwater amphipod Hyalella azteca. Can. J. Fish. Aquat. Sci. 43: 288-292.

Summers, P. and D.M. Whelpdale. 1976. Acid precipitation in Canada. Wat. Air Soil Pollut. 6: 447-455.

Summers, P.W., V.C. Bowersox and G.J. Stensland. 1986. The geographical distribution and temporal variations of acidic deposition in eastern North American. Wat. Air Soil Pollut. 31: 523-535.

Tang, A.J.S., A. Ahmed and M.A. Lusis. 1986. Summary: Some results from the APIOS atmospheric deposition monitoring program (1981-1984). Ontario Ministry of the Environment, ARB-110-86, APIOS-011-86: 33 pp.

Underwood, J.K. 1985. Acid deposition in Nova Scotia: seven years of record. Presented at the International Symposium on Acid Precipitation, Muskoka, September 15-20.

Venkatram, A. and P.K. Misra. 1988. Testing a comprehensive acid deposition model. Atmos. Environ. 22: 737-747.

Watt, W.D., C.D. Scott and W.J. White. 1983. Evidence of acidificiation of some Nova Scotia rivers and its impact on Atlantic salmon Salmo salar. Can. J. Fish. Aquat. Sci. 40: 462-473.

Whitby, L.M., P.M. Stokes, T.C. Hutchinson, and G. Myslik. 1976. Ecological consequence of acidic and heavy-metal discharges from the Sudbury smelters. Can. Mineralogist 14: 47-57.

Wright, R.F. 1983. Predicting acidification of North American lakes. Norwegian Institute for Water Research, Tech. Rep. 4/183: 165 p.

Yap, D. and J. Kurtz. 1986. Meteorological analyses of acidic precipitation in Ontario. Wat. Air Soil Pollut. 30: 873-878.

Zakshek, E.M. and K.J. Puckett. 1986. Lichen sulphur and lead levels in relation to deposition patterns in eastern Canada. Wat. Air Soil Pollut. 30: 161-169.

Table 1. Federal and Provincial Deposition Monitoring Networks in Canada.

Network	Period of Operation, Number and Location of Sites	No. of Sites (1986)	Sampling Period	Parameters Measured
Canadian Network for Sampling Precipitation (CANSAP)	Began in 1977 with 45 sites across Canada. Operation ended in January 1986. Network replaced by CAPMon.	0	Monthly samples collected on last day of month.	pH, conductivity, SO_4, NO_3, NH_4, Cl, K, Na, Ca, Mg.
Canadian Air and Precipitation Monitoring Network (APN)	Begain in November 1978 with 5 sites. 4 sites became part of CAPMoN.	1	Daily samples.	pH, SO_4, NO_3, NH_4, Cl, K, Na, Ca, Mg, total phosphorus.
Canadian Air and Precipitation Monitoring Network (CAPMoN)	Mid-1983 to present. Sites across Canada.	21	Daily precipitation samples. (8 locations also monitor air quality.)	pH, conductivity, SO_4, NO_3, NH_4, Cl, K, NA, Ca, Mg, alkalinity, acidity.
British Columbia Provincial Precipitation Monitoring Network	Began operation in 1983 with 7 stations.	12	Weekly samples.	pH, total acidity, total alkalinity, SO_4, NO_3, Cl, NH_4, Na, K, Ca and Mg.
Alberta Precipitation Quality Monitoring Network	April 1978 - present.	10	Monthly samples.	pH, acidity/alkalinity, conductivity, SO_4, NO_3, Cl, PO_4, NH_4, Na, K, Ca and Mg.
Summer Rain Sampling Network in Northern Saskatchewan	1983 - present.	7	Daily samples. (May 15 to October 15.)	pH, acidity, alkalinity, SO_4, NO_3, Cl, NH_4, K, Ca, Na, Mg, metal ions (2 samples/station/season).
Manitoba Network for Precipitation Collection	1980 (2 stations) - present.	6	Daily samples.	pH, conductivity, acidity SO_4, NO_3, Cl, Ca, NH_4, Mg, Na and K

Table 1. Federal and Provincial Deposition Monitoring Networks in Canada. (Cont'd)

Network	Period of Operation, Number and Location of Sites	No. of Sites (1986)	Sampling Period	Parameters Measured
Acidic Precipitation in Ontario Study (APIOS) Cumulative Network	September 1980 (monthly samples) - present.	37	28-day samples as of January, 1982.	pH, SO_4, NO_3, NH_4, Cl, K, Na, Ca, Mg, total Kjeldahl nitrogen, total phosphorus, trace metals.
Acidic Precipitation in Ontario Study (APIOS) Daily Network	September 1980 - present.	16	Daily samples.	pH, conductivity, SO_4, NO_3, NH_4, Cl, Na, Ca, Mg, acidity.
Acidic Precipitation in Ontario Study (APIOS) Cumulative Air Network	November 1981 - present	25	28-day cumulative samples.	Particulate SO_4, NO_3, NH_4, K, Na, Ca, Mg and trace metals. Gaseous HNO_3 and SO_2.
Acidic Precipitation in Ontario Study (APIOS) Daily Air Network	July 1980 - present.	4	Daily samples.	Particulate SO_4, NO_3 and NO_4, K, Na, Ca, Mg. Gaseous SO_2 and HNO_3.
Réseau d`echantillonage des précipitations du Québec	June 1981 - present.	42	Weekly samples.	pH, Ca, Mg, Na, K, NH_4, SO_4, NO_3, Cl, HCO_3, F.
New Brunswick Precipitation Monitoring Network	1980 - present	7	Monthly samples to October 1986. Weekly since then.	pH, acidity, alkalinity, conductivity, various cations, anions and metals.
Nova Scotia Precipitation Monitoring Network	1978 - present.	5	Weekly samples.	pH, acidity, alkalinity, conductivity, SO_4, NO_3, NH_4, Cl, K, Na, Ca, Mg an some heavy metals.
Newfoundland Environment Acid Precipitation Network	1980 - present	7	Weekly samples. (3 sites co-located with Environment Canada.	pH, alkalinity, conductivity, SO_4, NO_3, Cl, NH_4, Na, Ca, Mg and K.

Table 2. pH thresholds of biotic changes for selected Lake 223 organisms. (Modified from Mills and Schindler 1986)

Biota	Lake 223 pH
Mysis relicta abundance decline	5.93
Fathead minnow abundance decline	5.93
Mougeotia mats appear	5.64
Asterionella ralfsii appears	5.64
Orconectes virilis abundance declines	5.59
Lake trout recruitment ceases	5.59
White sucker recruitment ceases	5.02
Pearl dace abundance declines	5.09
Leeches become rare	5.09
Mayfly *Hexagenia* disappears	5.13

Table 3. Canadian Catchment Studies

Location	S Deposition (meq m^{-2} yr^{-1})	Duration of Studies	Monitoring Sites	References
Experimental Lakes Area (Ontario)	14[a]	1969-Present	5 lakes (control lakes for acidification experiments)	Schindler 1987, 1988
Turkey Lakes Watershed Study (Ontario)	54.8[b]	1981-Present	4 lakes, 26 streams	Jeffries et al. 1986 Semkin and Jeffries 1986
Muskoka-Haliburton (Ontario)	50-90[b,c]	1976-Present	8 lakes, 24 streams	Dillon et al. 1982 LaZerte and Dillon 1984 Seip et al. 1985 Dillon et al. 1987
Lac Laflamme Calibrated Catchment (Quebec)	46[a]	1980-Present	Lac Laflamme and 3 nearby lakes	Jones, H.G. and C. Deblois 1987
Kejimkujik (Nova Scotia)	34[a]	1978-Present	3 lakes	Kerekes and Freedman 1986; Kerekes et al. 1982

a) wet only
b) total
c) range from 1976 to 1986

FIGURES

Fig. 1. Acid rain: A national sensitivity assessment - a national evaluation of surface water resources at risk based on the potential of soils and bedrock to reduce acidity. (Source: Environmental Fact Sheet 88-1, Inland Waters and Lands Directorate).

Fig. 2 Anthropogenic emissions of SO_2 and NO_X in Canada in 1980. (Source: RMCC: Atmospheric Sciences, Aug. 1986).

Fig. 3. SO_2 emissions on (a) eastern Canada, and (b) the eastern United States, and NO_X emissions in (c) eastern Canada, and (d) the eastern United States. (Modified from Dillon et al. 1987).

Fig. 4. Annual sulphate deposition (Kg h^{-1} yr^{-1}) in eastern North America for the years 1981, 1982, and 1983. (Source: Summers et al. 1986).

Fig. 5 Relative importance of SO_4^{2-}, organic anions (A^-), and HCO_3^- ($+CO_3^{2-}$) in lakes in Ontario with conductivity <50 μS in six S deposition zones:

Zone 1, <0.25 gS m^{-2} yr^{-1};
Zone 2, 0.25-0.50 gS m^{-2} yr^{-1};
Zone 3, 0.50-0.75 gS m^{-2} yr^{-1};
Zone 4, 0.75-1.0 gS m^{-2} yr^{-1};
Zone 5, 1.0-1.25 gS m^{-2} yr^{-1};
Zone 7, >1.25 gS m^{-2} yr^{-1}.

Fig. 6. Annual alkalinity in the (a) ice-free, and (b) ice-covered season, and (c) pH in Plastic Lake, 1979-85.

Fig. 7 Location of Canadian catchment studies.

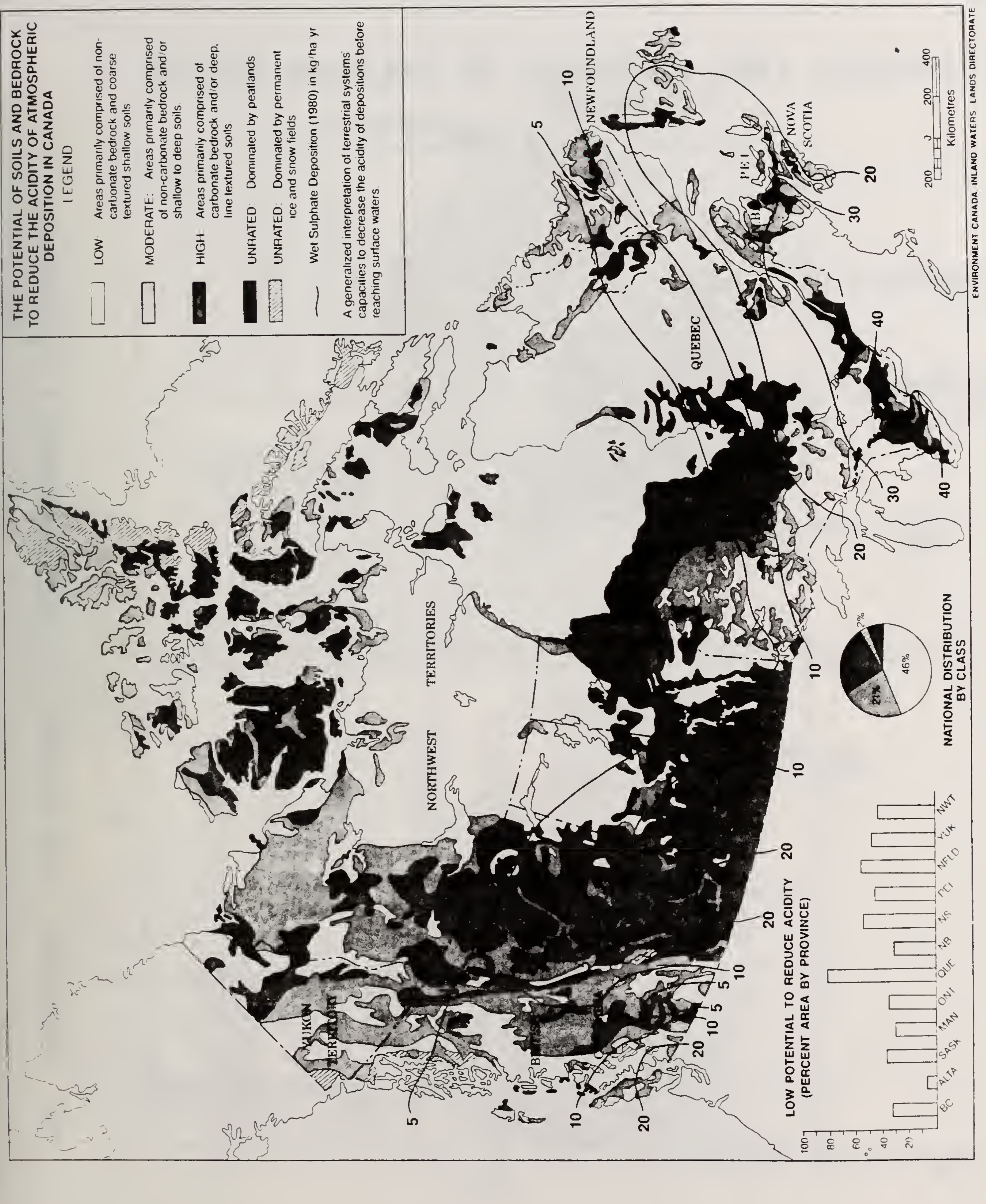
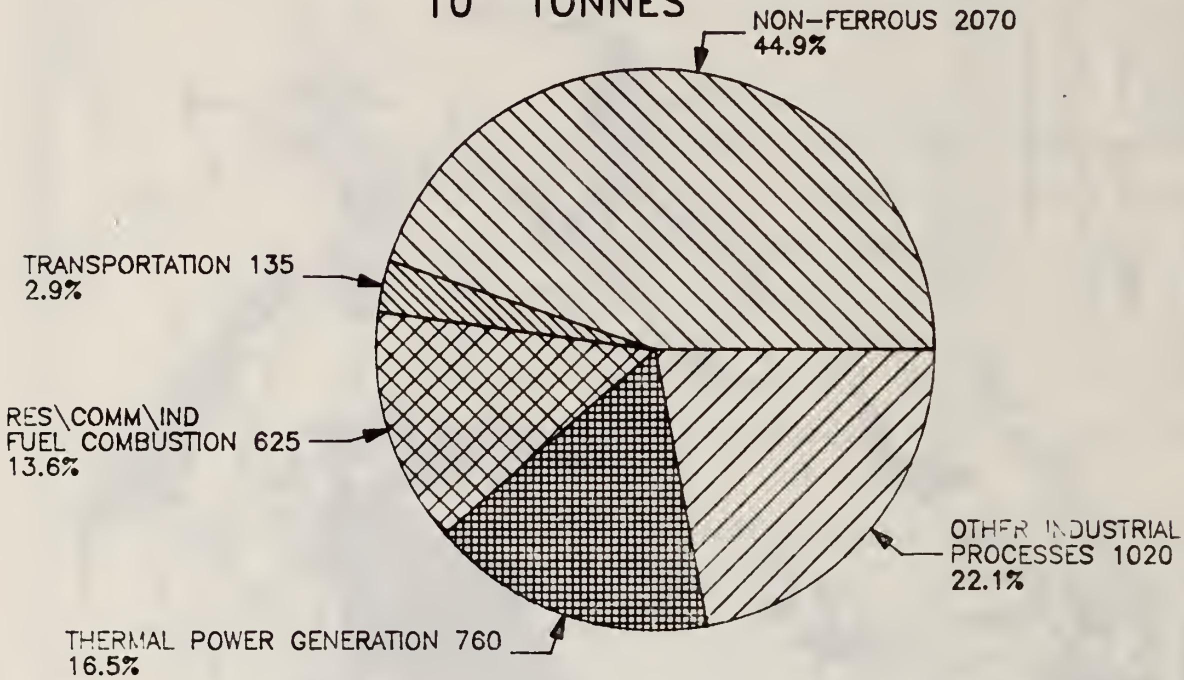

THE POTENTIAL OF SOILS AND BEDROCK TO REDUCE THE ACIDITY OF ATMOSPHERIC DEPOSITION IN CANADA
LEGEND
LOW: Areas primarily comprised of non-carbonate bedrock and coarse textured shallow soils
MODERATE: Areas primarily comprised of non-carbonate bedrock and/or shallow to deep soils.
HIGH: Areas primarily comprised of carbonate bedrock and/or deep, line textured soils.
UNRATED: Dominated by peatlands
UNRATED: Dominated by permanent ice and snow fields
Wet Sulphate Deposition (1980) in kg/ha yr
A generalized interpretation of terrestrial systems' capacities to decrease the acidity of depositions before reaching surface waters.
YUKON TERRITORY
NORTHWEST TERRITORIES
QUEBEC
NEWFOUNDLAND
NOVA SCOTIA
P.E.I.
LOW POTENTIAL TO REDUCE ACIDITY (PERCENT AREA BY PROVINCE)
BC ALTA SASK MAN ONT QUE NB NS PEI NFLD YUK NWT
NATIONAL DISTRIBUTION BY CLASS
46%
21%
2%
Kilometres
ENVIRONMENT CANADA INLAND WATERS LANDS DIRECTORATE

Fig. 1

CANADIAN 1980 EMISSIONS OF SULPHUR DIOXIDE
10^3 TONNES



CANADIAN 1980 EMISSIONS OF NITROGEN OXIDE
10^3 TONNES

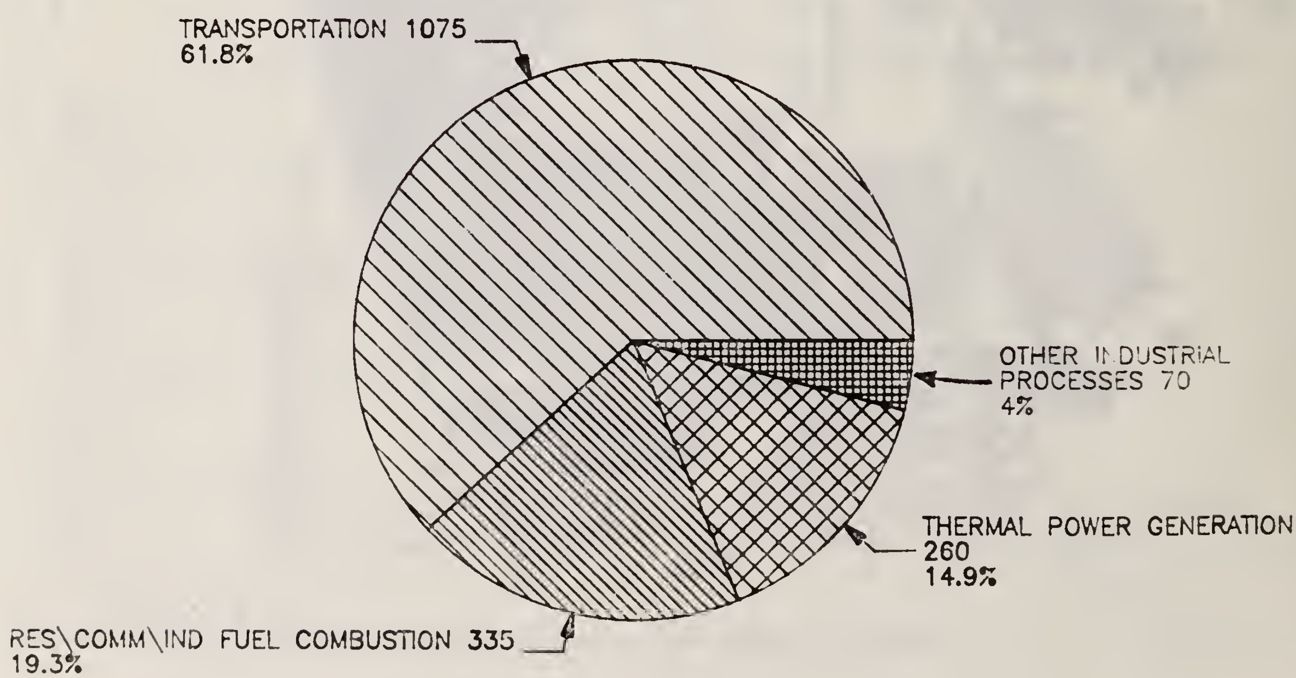
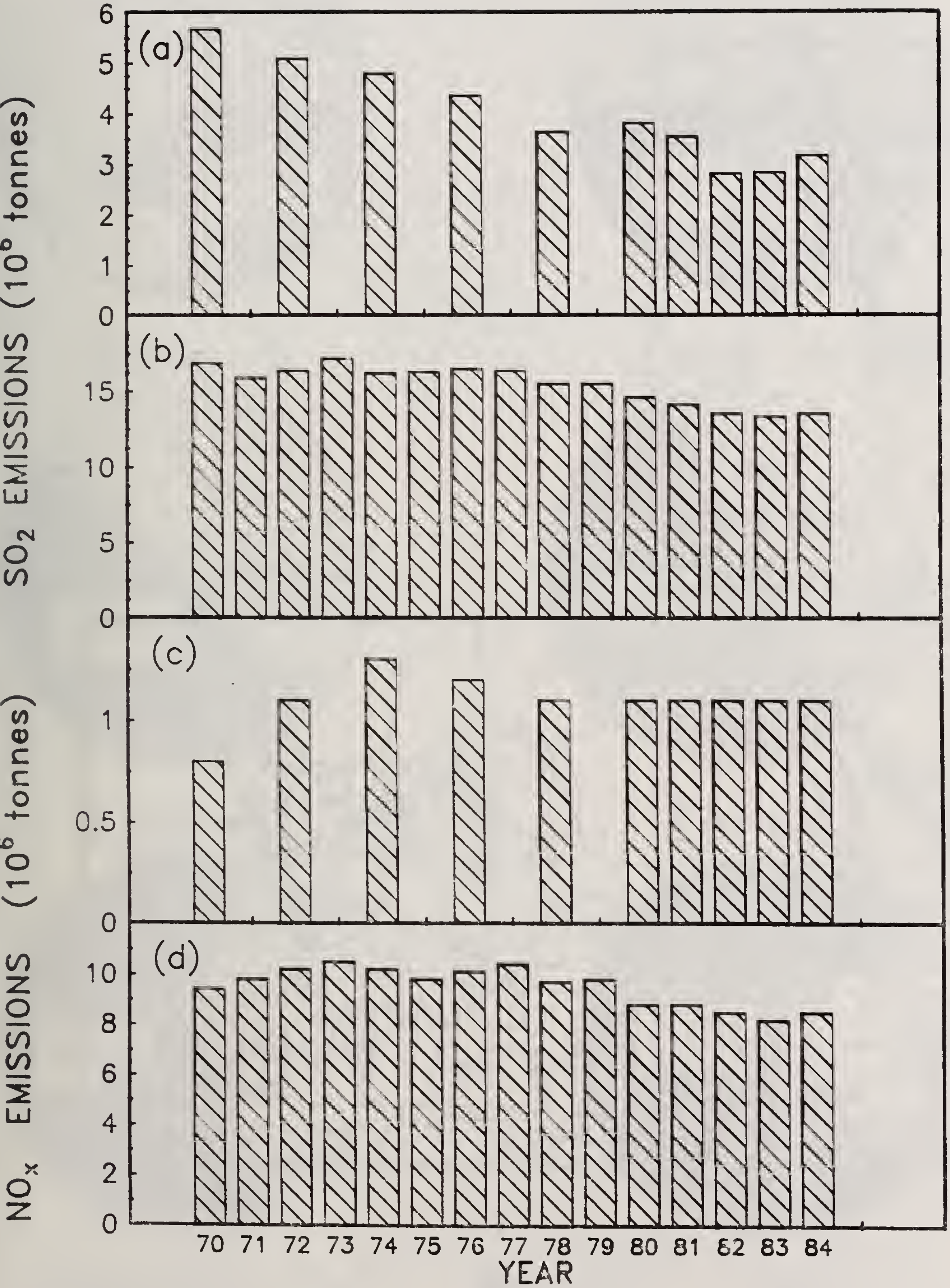


Fig. 2



SO_2 EMISSIONS (10^6 tonnes)
NO_x EMISSIONS (10^6 tonnes)
(a)
(b)
(c)
(d)
6
5
4
3
2
1
0
15
10
5
0
1
0.5
0
10
8
6
4
2
0
70 71 72 73 74 75 76 77 78 79 80 81 82 83 84
YEAR

Fig. 3

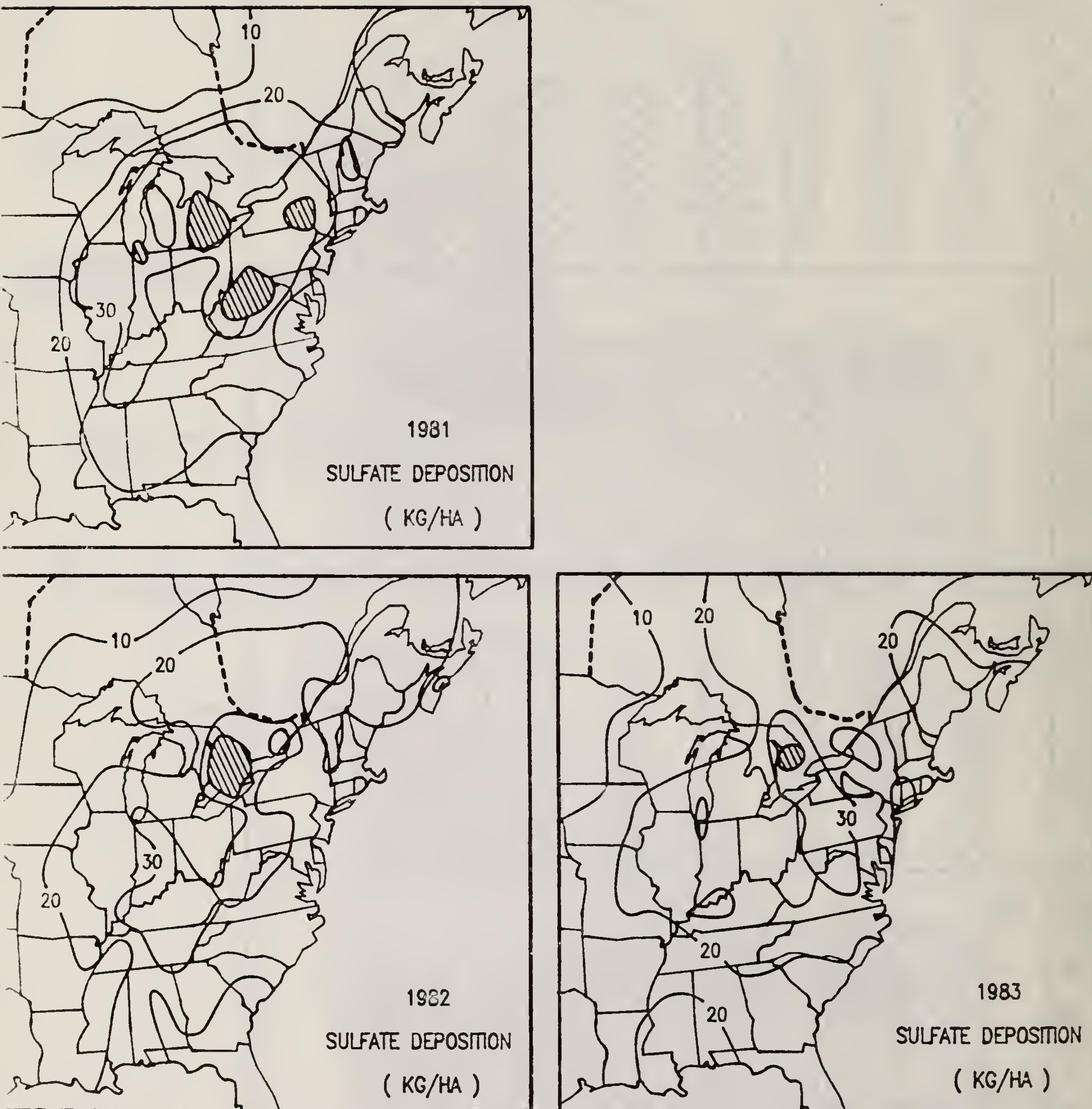

10
20
30
20
1981
SULFATE DEPOSITION
(KG/HA)
10
20
30
20
1982
SULFATE DEPOSITION
(KG/HA)
10
20
20
30
20
20
1983
SULFATE DEPOSITION
(KG/HA)

Fig. 4

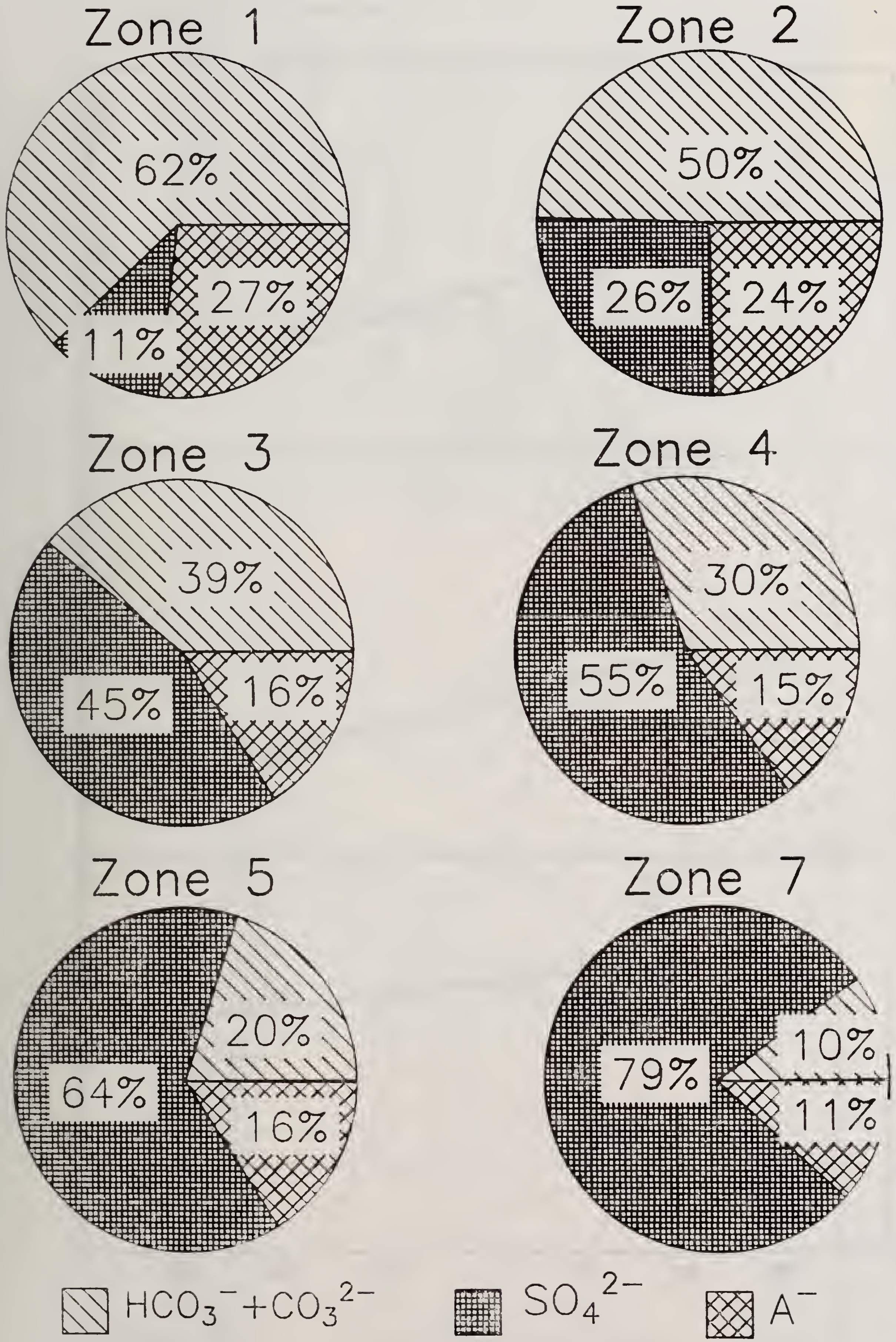
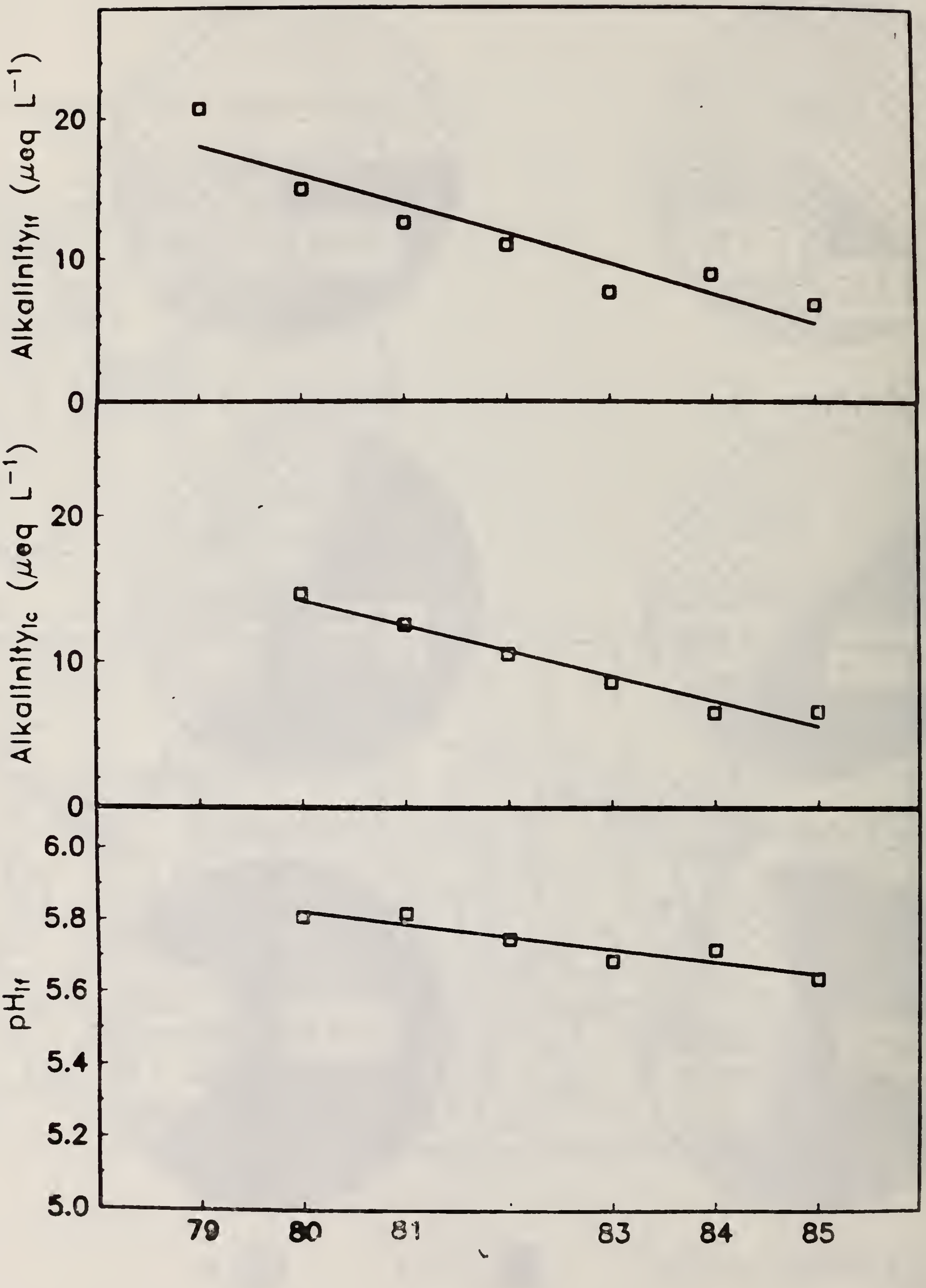

Zone 1
62%
27%
11%
Zone 2
50%
26%
24%
Zone 3
39%
45%
16%
Zone 4
30%
55%
15%
Zone 5
20%
64%
16%
Zone 7
10%
79%
11%
$HCO_3^- + CO_3^{2-}$
SO_4^{2-}
A^-

Fig. 5



Alkalinity$_{lf}$ (μeq L^{-1})
20
10
0
Alkalinity$_{lc}$ (μeq L^{-1})
20
10
0
pH$_{lf}$
6.0
5.8
5.6
5.4
5.2
5.0
79
80
81
83
84
85

Fig. 6

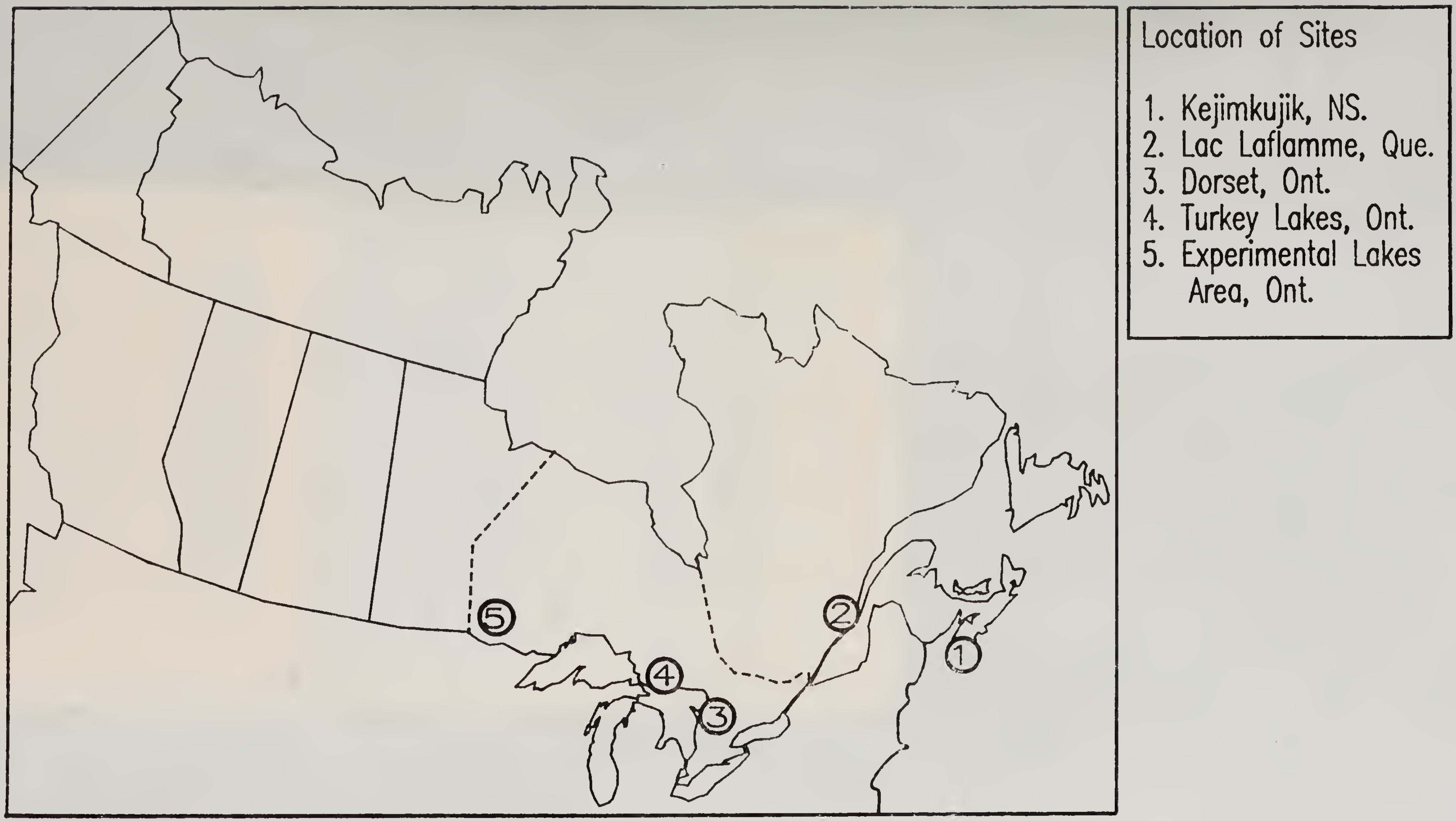

Location of Sites
1. Kejimkujik, NS.
2. Lac Laflamme, Que.
3. Dorset, Ont.
4. Turkey Lakes, Ont.
5. Experimental Lakes Area, Ont.
1
2
3
4
5

Fig. 7

DATE DUE

DATE	ISSUED TO
OCT 16 1989	J. SEMMLER - TR. ORG ✓
NOV - 7 1989	M POWELL - ITC ✓
NOV 2? 19??	HOPPER - ITC ✓